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Review

Incorporating energy justice throughout clean-energy R&D^5 in the United States: A review of outcomes and opportunities

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SUMMARY

It is widely acknowledged that a successful clean-energy transition is instrumental to climate change mitigation. However, clean-energy researchers and engineers rarely address the degree to which the success and consequences of the transition depend on its incorporation of equity and justice principles. In this review, we draw on inter-related literatures to discuss failures resulting from equity-myopic approaches to clean-energy research, development, demonstration, deployment, dispatch, and disposal (R&D^5) and explore opportunities, tools, and frameworks for energy practitioners to employ when attempting to incorporate justice into their work. We find that opportunities to incorporate energy justice are greatest at the earliest stages of the R&D^5 continuum. As inequities persist into later stages of R&D^5, they may lead to maladaptive technology development and the inequitable impacts thereof. We thereby articulate how embedding principles of energy justice throughout R&D^5 not only enables a successful clean-energy transition but also ensures that the transition is sustainable.

INTRODUCTION

In response to the Intergovernmental Panel on Climate Change's clarion calls regarding the pressing impacts of global warming,[1] governments and institutions worldwide have announced historic decarbonization goals, including achieving a carbon pollution-free power sector by 2035 and a net zero emissions economy by 2050.[2,3] To reach these targets, a major transformation of our energy infrastructure, technology, and built environment is required.[4,5] In their Net Zero by 2050 Roadmap, the International Energy Agency (IEA) calls for an unprecedented push for clean technology by 2030, comprising increasing global solar photovoltaic (PV) capacity 20-fold, wind power 11-fold, biogas and hydrogen production each 6-fold, zero-carbon-ready buildings 85-fold, and electric vehicle diffusion 20-fold between 2020 and 2050.[5]

Although each of these technologies has significantly lower life-cycle carbon emissions than incumbent fossil fuel technologies, reduced emissions alone do not make the technologies inherently just nor equitable.[6–8] A rich literature has emerged documenting where the development and deployment of clean-energy technologies have perpetuated existing inequalities or introduced new ones[9] and the ways in which these inequalities have slowed the progress of the clean-energy transition. For example, Baker chronicles how market-based wind farm development in Oaxaca,[10] one of the windiest places in the world, has resulted in conflict and displacement of Indigenous communities. Sunter et al. reveals that racial disparities in rooftop PV adoption persist even after accounting for differences in income and home ownership status,[11] limiting the benefits of this technology to the most advantaged groups. Further literature demonstrates that the disproportionate burdens borne by vulnerable communities are not merely confined to one or two aspects of the energy system, or to only specific technologies, but are present throughout.[12] In other words, burdens and injustices are persistent and systemic. This is not to say the existing fossil fuel-based energy system is equivalent to the future clean-energy system, although there have been attempts to co-opt calls for a just transition to justify continued use of fossil fuels,[13] but rather that systemic injustices have persisted over time. The clean-energy transition provides a unique opportunity to consider reimagining a more equitable and sustainable energy system.[14,15]

This review article terms approaches to clean-energy technologies that do not actively internalize energy equity or justice, such as the aforementioned examples from Baker[10] and Sunter et al.,[11] "equity-myopic approaches." Here, equity-myopic approaches rely on an assertion that purely technological or economic approaches to developing clean-energy technologies and pursuing a clean-energy system are sufficient for achieving

Box 1.

*Here, "complete" refers to efforts required to achieve net-zero emissions by 2050 outlined by the aforementioned IEA report, which has the goal of limiting global temperature rise to 1.5°C. IEA milestones include (1) "from today, no investment in new fossil fuel supply projects, and no further final investment decisions for new unabated coal plants." (2) By 2035, no sales of new internal combustion engine passenger cars. (3) By 2040, the global electricity sector has already reached net-zero emissions.

** "Sustainable" refers not only to "clean" and "renewable" energy production and usage on a life-cycle basis, but also in a manner that is able to be sustained. As defined by the UN Brundtland Commission in 1987, sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs."

a complete* and sustainable** (Box 1) energy transition. Here, we highlight that equity-myopic approaches are insufficient. By passively overlooking equity, equity-myopic approaches do not consider the real, persistent, and systemic biases that limit clean-energy access, affordability, and realization of the full benefits of the energy transition for those in poverty, the marginalized, and communities of color.

This review focuses on the six stages of clean-energy technology research, development, demonstration, deployment, dispatch, and disposal (R&D*5*) requisite for the clean-energy transition. This broad continuum is considered because without identifying and overcoming barriers to incorporation of equity and justice considerations throughout R&D*5*, we run the risk of developing and deploying maladaptive technologies that, by definition, inadvertently increase greenhouse gas (GHG) emissions, shift vulnerabilities, diminish welfare, and adversely impact marginalized and vulnerable groups by reinforcing inequities.[16] Manifesting in a similar fashion to Unruh's description of carbon lock-in,[17] maladaptive technologies and equity-myopic approaches lend themselves to "inequity lock-in"—the entrenchment and propagation of inequities in the energy system that must be addressed later on.

In this review, we enumerate the present and tangible ways that equity-myopic approaches to clean-energy technologies have perpetuated inequity lock-in and harms that ultimately limit the transition overall. We then offer opportunities for further embedding equity and justice considerations throughout R&D*5* to enable an accelerated, more sustainable, and more just energy transition. Given that landmark legislative actions in the United States, such as the Inflation Reduction Act,[18] will mobilize over a trillion dollars in the coming decade to enhance climate mitigation and adaptation efforts, the reviewed literature and implications of this article center the US. Although this review primarily focuses on the United States and mostly draws on literature from the Global North, we recognize the global nature of the energy transition and its equity implications, given that our global atmosphere and international supply chains demand the impacts of domestic decisions be evaluated beyond the restrictions of domestic borders.

The literature selected for this article was first identified through keyword searches on Scopus, the Web of Science, and Google Scholar using keywords such as "energy justice," "energy equity," "energy justice impacts," and "technology design," oftentimes in combination. The main challenge with identifying articles to investigate the impacts of integrating justice in early-stage energy research, development, design, and demonstration literature, particularly, was the latent nature of such topics.[19] For example, topics such as "justice" and "impact" or "effect" are polysemous (one word with multiple meanings) and synonymous (different words describe same idea)—making classic keyword searches on their own insufficient to identify literature for our purposes.[19] Therefore, tools such as ConnectedPapers.com and the Bibliometrix package in R were also used in tandem with forward and backward citation methods to aid in identifying relevant articles. Here, selected articles were based on the following criteria: the article either (1) speaks to the outcomes of equity-myopic approaches to clean-energy technology investigation, creation, or implementation or (2) provides resources or frameworks for technical energy researchers, engineers, and practitioners to better embed justice and equity in their work.

The analytic approach and structure of our review reverses the standard technology creation, implementation, and disposal timeline by beginning with the end of a technology's life and working backward toward early-stage research. In this manner, we highlight the equity impacts of prior stages. We find that opportunities to incorporate energy justice are greatest at the earliest stages of R&D*5* while inequities at these early stages lock-in and persist into subsequent phases. Incorporating equity and justice considerations in technological pursuits can have substantial implications on the course of the energy transition that we are just beginning to understand. More research is needed to understand the impacts of equity on both energy technology innovation and its outcomes, especially in different geographical, social, and political contexts.

CONTEXT

Although the literature does not yet offer a single definition of energy equity and energy justice, this article employs the following: energy equity refers to "the fair distribution of (social, economic, and health) benefits and burdens of energy production, distribution, and consumption and fair engagement in this system's decision-making processes."[20] Energy justice goes a step beyond to include retributive and corrective elements.[21] Energy justice is defined as "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system."[22] Energy justice is often conceptualized as encompassing distributive, procedural, and recognition tenets[23] and touching upon principles such as availability, affordability, sustainability, and inter-/intra-generational equity.[24] The literature's conceptualization of energy justice was built upon the more established fields of environmental and climate justice,[22] none of which exist in isolation.

Given the speed, depth, and breadth required for a successful energy transition,[25] it is especially important for us to better understand the trade-offs and tensions that arise between equity-centered approaches to technology development and historical and existing technical approaches and constraints.

As decision-makers attempt to juggle a multitude of priorities in the transition to a clean-energy system, considering equity and justice can appear as yet another task capable of ultimately slowing the transition down.[13,26] For instance, Heffron and McCauley highlight the ways in which particular just transition policy initiatives have been used to continue financing and prioritizing the fossil fuel industry.[13] These policy initiatives can act as an excuse to derail the energy transition by investing primarily in carbon-intensive regions. Additionally, Newell et al. discuss tensions policymakers face in pursuit of both a just and rapid low-carbon transition, especially given large, influential incumbent actors in the energy system.[26] These powerful incumbent actors have structural and financial resources to push forth large-scale change, despite potentially entrenching injustices.[26] Such resources have historically not been provided to support more grassroots decarbonization efforts and innovations. Both Heffron and McCauley and Newell et al. highlight the inefficiency of time-intensive, "for-show" participatory processes that tend to be ineffective and can act as delay tactics in the face of an urgent climate crisis.[13,26]

With energy justice literature concentrated in the social sciences and focused on later-stage technologies and interventions,[27] members of the technical workforce may be unclear to what degree, how, and when to apply energy justice to their work and if pursuing a just energy transition is, indeed, a responsibility to consider. Given the wealth of literature surrounding the need for equitable energy policymaking, we center our focus on the creation, use, and disposal of clean-energy technologies and the researchers, engineers, and other members of the technical energy workforce who study, create, build, use, and maintain these technologies and the resultant system. Here, we apply a perspective of systems justice[28] to elucidate the role of energy justice in successful clean-energy technology creation and implementation—seeing each energy scientist, engineer, and researcher as an actor in the larger energy system who has the potential to effect positive systemic change in the creation of a more just energy system. The utility of this cross-disciplinary review lies in its articulation of impacts associated with equity-myopic approaches to each stage of technology R&D[5] and its presentation of existing opportunities, tools, and frameworks for energy practitioners to employ for building a more just energy future.

WASTE GENERATION AND DISPOSAL

Research and development strategies do not always consider disposal; however, the development and selection of materials, establishment of manufacturing and recycling processes, and the ultimate disposal of waste products often drive the justice implications of a technology. Siting of waste facilities, lack of inspections,[29] toxicity of manufacturing and disposal processes, and mishandling of waste result in adverse impacts that have historically disproportionately affected low-income communities, communities of color, and immigrant communities.[30–32]

In 1987, Dr. Robert Bullard and the United Church of Christ Commission for Racial Justice published their seminal report exposing that toxic waste landfills were sited primarily in communities of color throughout the nation.[30,31] Their follow-up report in 2007 showed that race continued to be a stronger predictor of hazardous waste siting than income, education, and other socioeconomic indicators.[31] Although there exist policies, governing bodies, and programs dedicated to hazardous waste assessment,[33] cleanup,[34] waste site maintenance,[35] and enforcement of environmental justice laws,[36] research has found evidence that counties with larger populations of Black residents and counties with higher residential instability, higher population densities, and larger populations of foreign-born residents have disproportionately fewer inspections under federal waste handling laws.[29]

A 2020 US Environmental Protection Agency (EPA) report indicated that 21 million people in the US live within 1 mile of a Superfund site—a location contaminated by hazardous waste that has been designated by EPA for management and clean up—and that they are disproportionately minority, living below the poverty level, and linguistically isolated.[32] Further studies show that the presence of a nearby Superfund site is associated with reduced life expectancy, elevated cancer risk, and increased congenital anomalies.[37–39] In 2019, the Government Accountability Office found that 60% of Superfund sites may be impacted by climate change effects including flooding, storm surges, wildfires, and sea level rise, potentially leading to releases of contaminants that could pose even greater risks to the health of the surrounding communities.[40]

Clean-energy technologies and processes are not immune from these issues. For example, some solar panels contain lead and cadmium, which, when present in high enough quantities, can be considered hazardous waste under the EPA's Resource Conservation and Recovery Act (RCRA) at end-of-life disposal.[41] The IEA projects that there will be 10 million metric tons of cumulative PV waste in the US and 78 million metric tons worldwide by 2050. Although this is a small fraction of the waste produced by fossil fuels,[42] it still points to a need for end-of-life management approaches, including regulations, research into methods of materials recovery, and increasing capabilities for reuse and recycling.[43,44] Similarly, a predicted 4 million metric tons of lithium-ion electric vehicle batteries will reach the end of their useful life annually by 2040 in the US.[45] Lithium-ion batteries are often regulated as hazardous waste under RCRA because they contain flammable electrolytes and can exhibit hazardous characteristics of reactivity.

Research into new processes for hard-to-recycle materials, such as thermoset epoxy resins in wind turbines,[46] and early-stage design interventions, such as "design for recycling,"[47] seek to address the need for more effective reuse and recycling of energy technologies and their associated materials. Consideration of waste and disposal at the earliest stages of research and development can impact material selection, future manufacturing processes, waste handling, and the effects of disposal, all of which impact the energy equity and justice implications of the technology through all phases of R&D[5]. Designing for a circular economy—which includes developing novel, low-emissions materials, creating design architectures to increase recyclability, designing manufacturing processes that reduce materials use, increasing technology lifetimes, and developing end-of-life material recovery strategies[47]—reduces the potential impacts of waste and disposal on low-income communities and communities of color, while also potentially addressing the supply-chain stress that is anticipated with the unprecedented global scale-up of clean-energy technology deployment.[45,47,48]

DISPATCH

Although dispatch—instructions to generators, transmission facilities, or other electricity market participants to start up, shut down, raise, or lower generation—is a concept most familiar in electricity grid operations, here, it also encompasses how energy systems are operated during their working lifetimes. In between the deployment of technologies in specific locations and their decommissioning and disposal, many energy technologies have lifetimes of 30–100 years (e.g., solar and hydropower, respectively).[49] During these long technical lifetimes, energy systems can be operated in alternate ways that can mitigate or magnify potential harms.[50] Early incorporation of equity and justice principles into dispatch decision-making could lead to different determinations that not only enable more just outcomes but also reduce social and health costs, overall.

Energy planners can include a carbon price in modeling efforts as a first step toward reducing emissions, but equity also requires understanding for whom emissions are reduced.[51] Studies in North America find that adding a carbon price to least-cost capacity expansion and operation modeling induces changes to the optimal technology deployment types, timing, and capacity installed, in addition to dispatch patterns.[52] However, even where models incorporate a price for GHGs, rarely is it comparable to the $185 USD per metric ton CO_2 estimate for the social cost of carbon—the total monetized value of the damages to society caused by an incremental metric ton of CO_2 emissions—recommended by Rennert et al.,[53] or the $120–$340 USD per ton CO_2 estimated by the EPA.[54] Yet, the social cost of carbon itself does not address other air pollutants, such as particulate matter, sulfur oxides, nitrogen oxides, volatile organic compounds, and ozone, which have more direct health impacts on local populations and, because of historical siting decisions, are more likely to negatively impact disadvantaged groups.[55,56] For example, one study found that reducing transportation-related emissions in Los Angeles would disproportionately benefit disadvantaged communities because those communities were located closest to the pollution sources.[57]

Kerl et al. modified the traditional approach to optimal electricity planning and dispatching by incorporating air quality modeling, fluctuating pollutant emissions, and the resultant health impacts that are locationally and temporally specific. They found that incorporating health externalities beyond the global pollutant of CO_2 on a life-cycle basis changes technology choices and dispatching, resulting in a lower overall social cost.[58] The case study primarily replaced coal with gas-powered generation in the state of Georgia. Since their study period, coal-fired electricity generation has dropped precipitously nationwide, and there is increasing interest in retrofitting retired coal infrastructure; however, less-polluting resources, such as biomass and wood combustion, are not exempt from mortality impacts. As of 2018, the projected mortality impacts of particulate matter-related wood and biomass combustion in energy consuming sectors—residential buildings, commercial buildings, industry, and electricity—are higher than the impacts of coal or gas combustion,[59] thereby necessitating the continued inclusion of health equity even in clean electricity dispatch decisions.

Beyond day-to-day operations, decisions on dispatch, load shedding, and selective restoration made during extreme events reveal both disparities and opportunities to further embed equity principles. Recent literature on grid operations during climate emergencies has revealed significant inequities in whose power gets shut off first and whose power is restored last. These patterns have been documented during hurricanes in Puerto Rico,[60] heat waves in California,[61] and winter storms in Texas.[62] The increased number and duration of outages for low-income and minority groups during climate emergencies compound with issues of lower resilience resulting in worse health and economic outcomes, including increased risk of mortality. Integrating equity considerations into dispatch decisions during power shutoffs and restoration can help address this discrepancy by adjusting the location of load shedding and order of restoration to ensure disadvantaged communities do not unduly experience more frequent or longer power disruptions.[63]

Clark et al. present a novel, theoretically grounded, framework to quantify the social burden of infrastructure disruptions.[64] Utilizing a Capabilities Approach theory to human development, their metric focuses on "estimating the burden of post-event adaptations taken by households to maintain their basic capabilities (e.g., ability to access food and water) and fulfill important household functionings (e.g., maintaining health and well-being)." Such a metric allows for clean-energy dispatch decision-makers to internalize not only the social cost of carbon and air pollution, but also differential resource access and vulnerability into their prioritization decisions. Furthermore, studies on hidden energy poverty explore the adaptations taken by lower-income households every day (not only during infrastructure disruptions) to limit their energy consumption to reduce financial stress.[65] Decision-makers can work with communities to understand how these behaviors, along with disparities in other indicators of well-being,[66] may impact dispatch and load shedding decisions. Ensuring more equitable dispatch decision-making and system controls inevitably relies on the existing infrastructure and choices made during technology deployment, particularly choices during siting processes, ultimate siting locations, and the distributional impacts thereof.

DEPLOYMENT

The enormity of the net zero challenge relies on large-scale clean-energy technology deployment, entailing siting and construction of infrastructure and widespread adoption of end-user technologies. For instance, the IEA estimates that 55% of the cumulative emissions reductions in the pathway to net zero by 2050 are linked to consumer choices, such as purchasing an electric vehicle, retrofitting a house with energy-efficient technologies, or installing a heat pump.[5] With 28% (23.1 million) of homes in the US owned and occupied by people of color,[67] and approximately 31% (140 gigawatts [GW]) of rooftop solar potential on residential rooftops owned and occupied by people who earn very low to moderate income,[68] discussion of the potential role and impact of these groups in technology adoption and the broader energy transition have risen to the forefront.

Often, skepticism about integrating equity considerations into the clean-energy transition focuses on the deployment stage with concerns about whether procedural justice—ensuring that impacted communities play a meaningful role in the decision-making process—will slow the process of deployment. Newell et al. discuss barriers and tensions that arise between rapid, large-scale decarbonization and pursuing procedural justice in the energy transition given existing power and resource structures.[26] First, they highlight a need for greater clarity around "which issues and for whom enhanced citizen engagement works well," given uneven opportunities for citizen engagement and a tendency for privileged, wealthy, and more educated groups to dominate in participatory processes.[26] A lack of meaningful commitments to communities and insincere motives for pursuing citizen consultation also delays progress. Second, Newell et al.[26] discuss how incumbent firms, such as large utilities, banks, construction companies, car manufacturers, and so on, have technical, financial, and organizational resources to deploy technologies more quickly and at larger scales than grassroots innovators. Yet, incumbent firms have historically prioritized wealthier consumers and short-term investments, neglecting opportunities available through pursuing energy justice.

The historic buildout of much of the US current infrastructure, which was funded by significant public investment, occurred with little consideration to community impacts, equity, or justice, leading to continuing systemic disparities that limit the future transition. For instance, Brockway et al. reveal that grid infrastructure limits—resulting from prior grid maintenance and upgrade decisions—exacerbate inequalities in current adoption rates further reducing future access to new solar PV capacity for Black-identifying and disadvantaged census blocks.[69] These infrastructure limits not only cause disparities in access for certain demographic groups, but also hinder the state of California's ability to achieve its electric vehicle adoption and residential load electrification goals necessary for a rapid clean-energy transition.

In addition to the toxic waste landfills mentioned previously,[30,31] many types of noxious power plants and other energy infrastructures were disproportionately sited in communities of color throughout the nation.[70] In many cities, highway construction destroyed communities of color, and in the 1950s and 1960s, thousands of homes disproportionately occupied by Black and Latino families were torn down in the name of "urban renewal" without due process or procedural justice.[71] Such rapid yet unjust deployment processes of the past are not possible under the National Environmental Policy Act (NEPA) and many similar state and local laws[72] that are critical to due process in our democratic society.

Given that local, state, and federal laws require the participation and consideration of potentially impacted environmental justice communities, better incorporation of equity considerations in deployment processes can result in more successful technology implementation. Case studies and analyses of deployment activity outcomes show both aligning with community values—such as trust, justice, equity, and fairness—and addressing community concerns bolster successful implementation.[73–76] For example, meaningfully embedding aspects of procedural justice through community-based consultation and decision-making and enabling opportunities for communities to financially participate in wind turbine deployment has been associated with successful outcomes.[77,78]

On the other hand, mobilizations against clean-energy projects when community concerns are not considered from the outset can hinder transition efforts by delaying deployment, slowing the phase-out of carbon-intensive energy systems, eliciting costly settlements and protests, and causing changes to design and policy at the time of deployment.[79] Boudet reviewed public reactions to new energy technologies, noting the need to understand interconnected roles of technology, people, place, and process.[74] Given increasing likelihood of people and place-based factors playing an outsized role in shaping public perceptions of energy technologies, Boudet highlights that "understanding and adapting technologies and decision-making processes to a particular place and people will become increasingly important for the successful deployment of new energy technologies."[74]

Decisions made upstream of deployment, such as a project's size and visual impact, have also been shown as factors influencing the energy justice outcomes and community opposition to renewable energy technology deployment across the literature.[73,75,80,81] In addition to a technology's form and function, taking dimensions of equity, justice, and fairness that enable successful deployment into account as early as possible in energy technology research, development, demonstration, and design activities provides an opportunity to better consider how to enhance symbiosis between human needs and technology.[82] Enhancing and streamlining compatibility in this manner has the propensity to minimize opposition and the need for late, less impactful, and costly changes[83] in response to said opposition.

DEVELOPMENT AND DEMONSTRATION

The development and demonstration stages of the R&D[5] continuum provide unique opportunities to ground technology design and evaluation in justice considerations and the full diversity of end-user preferences to facilitate successful deployment.[82,84] Here, development encompasses technology design from conceptualization to realization, whereas demonstration is considered design validation in relevant environments to prepare for deployment. Decisions made when designing technologies are immensely important to the outcomes of the technologies. Design decisions at the earliest stages not only determine the ultimate form and function of energy technologies, but they also solidify costs—with an estimated 80% of manufacturing costs determined at the design stage.[85,86] Further, these technical design decisions also establish the values, winners, and losers associated with those technologies.

Given development and demonstration activities solidify the form and function of technologies, it is at these design-intensive stages that the incorporation of values and assumptions in the technology itself is most salient.[87,88] At these stages, the values that drive deployment success, such as equity, fairness, and community altruism, can be considered to allow for more

Box 2.

NSF Broader Impacts are defined as "the potential to benefit society and contribute to the achievement of specific, desired societal outcomes." (https://www.nsf.gov/pubs/policydocs/pappg18_1/pappg_3.jsp#IIIA2b).

streamlined technology implementation. Elucidating values and assumptions that drive design decisions also provides clarity regarding which members of the population are considered in technology development and demonstration.

Understanding these values and assumptions is important to avoid making brittle decisions during development and demonstration that will propagate through subsequent stages of R&D*5*. "Brittle decisions" are defined as those that are "optimal for a particular set of assumptions but that perform poorly, or even disastrously, under other assumptions."[89] An example of brittle decision-making is the forced replacement of traditional Alaska Native homes with poorly insulated, fossil-fuel-dependent Euro-American wood-frame houses, which has created continued energy and food security issues and high energy burdens for Alaska Natives.[90] Methods such as user-centered design, participatory design, and universal design provide ways to avoid making brittle decisions.

User-centered design is an overarching term used to describe design processes in which end-users guide or influence the ultimate product outcomes.[91] Across the literature, user-centered design processes have been used to avoid brittle decision-making that does not consider the diverse array of end-users or their settings. Adequate technology development and design requires accurate understandings, rather than assumptions, of the context in which the technology will be used. For example, user-centered techniques have been used to address failures associated with technological approaches to "improved cookstoves" for developing countries. Prior research focused on technically improving cookstove combustion and fuel efficiency under the assumption that improved efficiency would have both economic and ecological benefits for households, and dissemination of these improved cookstoves was alone sufficient to achieve adoption and sustained use.[92] However, these improved cookstoves repeatedly failed to gain widespread adoption because they did not meet the needs of the primary users who found the cookstoves difficult to install, more time-intensive and cumbersome, and incompatible with locally available cookware.[92,93]

To ensure adoption and sustained use, researchers and engineers have increasingly focused on strategies for clean cookstoves development and dissemination that are tailored to the needs and preferences of end-users. Beyond increased adoption, user-centered techniques have been associated with improved ecological outcomes for clean cookstoves. Gill-Wiehl and Kammen demonstrate that a cookstove strategy that prioritizes the health of end-users (even one that results in the increased use of liquefied petroleum gas [LPG]—a fossil fuel) leads to net reductions in GHG emissions.[94]

Participatory design describes design processes that involve the users as co-designers during technology development.[91] Based on commitments to democracy, empowerment, mutual learning, and skillfulness, participatory design not only affects technological outcomes but may also engender organizational change, new practices, and insights.[95] Participatory methods have been used in energy system modeling and planning to better understand community perspectives, build trust, and ensure more robust research results.[96] These methods have also been used to co-design culturally compatible and sustainable housing with Indigenous communities.[97]

Whereas participatory design methods focus on localized, context-based innovation, universal design creates systems, products, and environments made to be used by all people without a need for customization or specialization.[98] Oftentimes, universal design is employed when making devices more accessible, but it can also be applied to infrastructure as we strive to create disability-inclusive climate resilience strategies.[99] Upstream of early-stage development and design, community-based participatory research has also been associated with enhanced intervention quality and increased community capacity.[100,101] Ultimately, development and demonstration activities are informed by the research that precedes these stages, making the findings, decisions, and recommendations of researchers particularly important for ensuring equitable technology design, manufacturing, and implementation.

RESEARCH

Whether basic or applied, research, which can be considered systematic investigation and early-stage technology conceptualization, provides direction for every other stage of R&D*5*. We cannot assume that today's energy research will inevitably benefit society as a whole many years down the road—especially without better understanding the social, political, economic, and cultural contexts in which research is undertaken and technology is developed.[102,103] The need for equitable energy technology research is beginning to gain traction with discussions of equitable funding opportunities and more inclusive practices and engagement in technology development rising to the forefront.[104] Funders are increasingly recognizing the importance of integrating social science in energy research to understand opportunities and barriers to equitable adoption of clean-energy technologies.[102,104] Funders also play a major role in reconciling the inequitable distribution of benefits in research funding. For example, Woodson et al. analyzed National Science Foundation (NSF) sponsored nanotechnology grants from 2013 to 2017 to identify how the benefits of these projects were distributed. They found that work tended to directly benefit "advantaged" groups.[105] Even when researchers analyzed a larger set of NSF Broader Impacts (Box 2) statements across various research areas, Broader Impacts statements seeking to benefit advantaged groups were more frequently identified than those seeking to benefit marginalized groups.[106]

Moreover, when researchers discuss equity, it is important to consider who is included and excluded from defining what is, indeed, considered "equitable."[107] Values that drive technology development—be they values of those funding the research, those doing the research, or the institutions for which they work—in the energy transition are not inherently neutral.[88,108]

When considering values imbued in clean-energy technology, research informs all other stages of the R&D^5 continuum. From the earliest stages, researchers and funding agencies determine technological possibilities and concepts worth exploring. These values may emerge in overt ways, such as an institution, research group, or engineering team explicitly communicating and incorporating values into the technology they are developing,[109,110] or values could emerge in more covert ways as biases in systems, processes, and technologies.[111]

Friedman and Nissembaum characterized bias in computer systems that can extend to other systems—for our purposes, the energy system.[111] They define biased systems as those "that systematically and unfairly discriminate against certain individuals or groups of individuals in favor of others. A system discriminates unfairly if it denies an opportunity or a good or if it assigns an undesirable outcome to an individual or group of individuals on grounds that are unreasonable or inappropriate."[111] They introduce three types of biases for researchers, engineers, and designers to consider as they are developing technologies: preexisting bias, technical bias, and emergent bias.

Preexisting bias has its roots in social institutions, practices, and attitudes. It exists in the context of the wider society and likely influences the technology designer. The historical exclusion, devaluation, and resulting underrepresentation of minoritized groups and women in the research enterprise despite well-documented benefits of diversification[112,113] can be considered an example of preexisting bias. Technical bias arises from technical constraints or considerations; this bias is inherent to the design of the technology itself. The economic, social, and ecological issues surrounding cobalt in lithium-ion batteries demonstrate impacts of technical bias in research due to early-stage material selection.[114–116] Critical materials needed for batteries (cobalt, lithium, nickel, graphite, and manganese) are finite and mined in only a few regions of the world, which are often in countries with less-stringent environmental and human health regulations[45]—further demonstrating the health consequences of domestic energy decisions on vulnerable communities across the globe. Finally, emergent bias, such as the disproportionate impacts of climate change on low-income populations and communities of color,[117–119] arises in the context of the technology's use.

To manage biases in energy research, and subsequent R&D^5 stages, it is important to acknowledge the existence of these biases and seek to address these technological shortcomings because such actions are fortified when there is support from the larger professional community.[111] Traditional approaches to make research more equitable include attempts to diversify research teams, engage a broader range of stakeholders, promote inclusive policies and practices, and disseminate research findings more widely. Now, there exist more tools and resources to better incorporate ethical concerns, concerns of equity, and concerns of justice into energy research. Options range from pursuing interdisciplinary research from the earliest stages[102] to engaging and co-creating with communities and better orienting equity throughout all stages of energy research and design.[120]

Tools that can facilitate consideration of potential inequities early in the process include: the Justice Underpinning Science and Technology Research (JUST-R) metrics framework,[121,122] green chemistry,[123] and agent-based modeling,[124,125] among others.[126–128] Additionally, more dynamic and inclusive modeling, which may include a range of models, such as climate models, behavioral models, cost projections, along with demographic data,[129] can inform the design of more holistic and robust research and development activities that subsequently affect later stages of R&D^5. As researchers, scientists, and engineers, taking action to minimize biases and avoid making "brittle decisions" in research design, technology development, and subsequent deployment can enable us to do more equitable and far-reaching work.

GAPS AND FUTURE DIRECTIONS

From this literature review, we recognize that incorporating equity and justice considerations into technological pursuits can have substantial implications on the course of the energy transition that we are just beginning to understand. Here, we see that at earlier stages of the R&D^5 continuum, there were fewer studies on justice considerations in technical work in the energy field, specifically. Although there is increasing focus on energy justice considerations in technical energy research, as exhibited in the article by Ratcliff et al. on soft materials for photoelectrochemical fuel production,[130] an opportunity exists for deeper consideration of justice at these early stages of R&D^5. Additionally, more research is needed to understand the impacts of equity on both energy technology design and its outcomes, especially at the earlier stages of research, development, and design. In this area, we see several existing knowledge gaps worthy of exploration. The literature can benefit from longitudinal studies on the impacts of equity-informed technology development, providing greater understanding of how equity considerations traverse and influence each stage of R&D^5. Further, it will be important to evaluate proposed frameworks and practices for integrating energy justice across technology R&D^5 in different geographical, social, and political contexts.

Decision science studies can provide much needed insight into how we view, assess, prioritize, and address risks to frontline communities in transition and mitigation efforts—drawing from both contemporary and historical perspectives. For example, integrating traditional ecological knowledge held in native communities could reframe and reform our approaches to sustainable development, relationships with our environment, and the development of our energy systems.[131,132] Furthermore, greater understanding of how clean-energy innovation can grapple with restorative justice, which aims to repair harm done to individuals, communities, society, and ecosystems,[133] appears to be a major gap in the literature that warrants further study. Energy inequities look different in different parts of the world, resulting from different histories of development, and therefore restorative justice approaches may vary across intra- and international boundaries. Furthermore, as we pursue energy justice in the US, we should be careful not to unintentionally create energy injustices elsewhere. Grappling with the multiscale, systems-level dimensions of energy justice, especially in the hopes of full domestic decarbonization, remains a challenge worthy of further exploration.

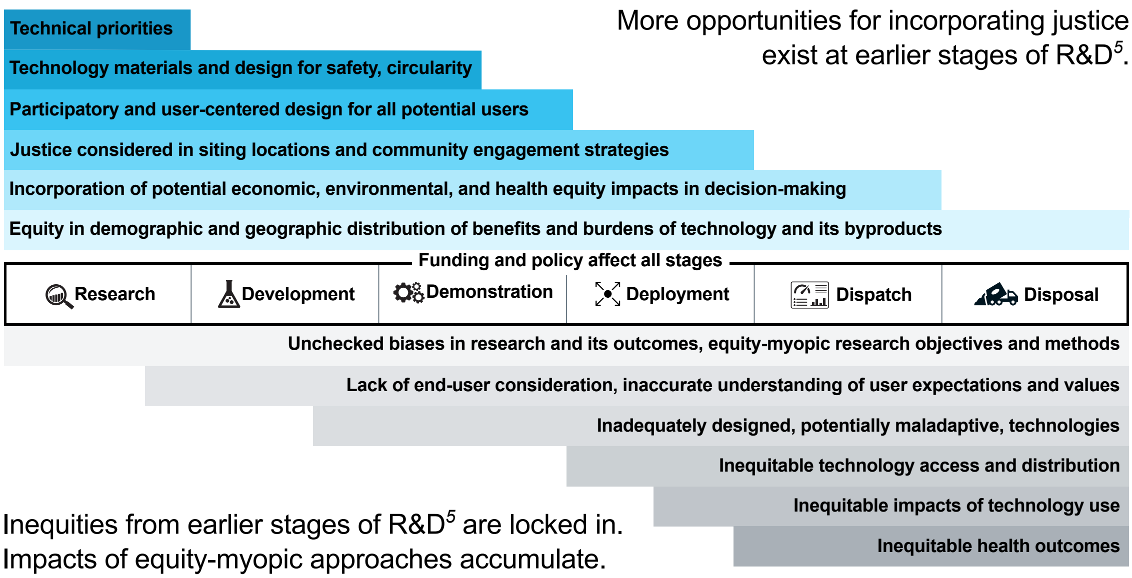

Figure 1. Opportunities to incorporate justice and compounding inequities across R&D[5]

Opportunities (top) available for incorporating energy justice throughout clean-energy R&D[5], which are most numerous at earlier stages, and outcomes (bottom) of equity-myopic approaches that accumulate throughout the R&D[5] continuum. More equitable policymaking and funding opportunities incentivize and shape more equitable technology creation and implementation; therefore, these elements are shown to affect all stages of R&D[5]. Figure informed by literature found in Tables SA.1–SE.2.

CONCLUSIONS

A complete and sustainable clean-energy transition will likely depend not only on equitable energy policymaking but also on the incorporation of energy justice throughout all stages of R&D[5] by the researchers, engineers, and the clean-energy workforce who create, build, use, and maintain energy technologies. Given that energy justice and equity allows us to effectively streamline context-specific,[103] user-centered technology development and deployment, we recognize early and intentional incorporation of equity and justice principles in clean-energy R&D[5] can both engender more just outcomes and push the clean-energy transition forward overall. Particularly in the context of a democratic society, minimizing barriers to both technology acceptance and diffusion by mitigating bias and harms to vulnerable communities propels the clean-energy transition and better ensures we are not prioritizing maladaptive, short-term solutions in our urgent creation of a long-term energy system.[134]

Siloed approaches to adaptation and mitigation strategies are often found to be ineffective, especially if these strategies do not address underlying drivers of vulnerability.[16] As we navigate the tensions and trade-offs inherent to pursuing a broad and deep energy transition,[25] a wider systems-level perspective of equity throughout all stages of R&D[5] can act as a means to relieve anticipated tensions related to the substantial technological, ecological, economic, and social changes expected due to the energy transition. Equity-centric techniques can enable more context-specific technological development and provide a broader view of the potential impacts of our technical decisions. For example, climate resilience development pathways integrate adaptation and mitigation measures to advance sustainable development for all.[16,135] Along with ecological, energy, and societal considerations, a key aspect of climate resilient development is equity. Climate resilient development processes link several sources of knowledge, such as scientific, Indigenous, and local knowledge, to create more locally appropriate, relevant, and sustainable outcomes, which further accelerates and deepens system transitions by overcoming jurisdictional and organizational barriers.[16]

A lack of equity and justice incorporation throughout R&D[5] not only exposes us to the risk of delaying a successful energy transition, but also to the compounding effects of inequity lock-in, which can result in the development and deployment of maladaptive technologies. Beyond their moral and ethical shortcomings, maladaptive clean-energy technologies are inherently less effective as sustainable solutions because they further entrench inequities in the energy system, leading to issues that will eventually require subsequent action in the form of less impactful, more costly late-stage solutions.[16,79,83,134] From this synthesis of inter-related literatures, we see that inequitable outcomes are not necessarily inevitable, and the pursuit of a just energy transition requires deliberate efforts from the earliest stages of technology development. At the earliest stages of the R&D[5] continuum, opportunities to incorporate justice in clean-energy R&D[5] are most plentiful because early-stage outcomes influence subsequent stages (see Figure 1). Yet, at these early stages there is likely more uncertainty about future outcomes,[122] leading to the need for more robust research into the long-term effects of embedding equity at these early stages of energy technology creation.

As large, complex infrastructures that are planned, built, and used over long time frames, many clean-energy systems are

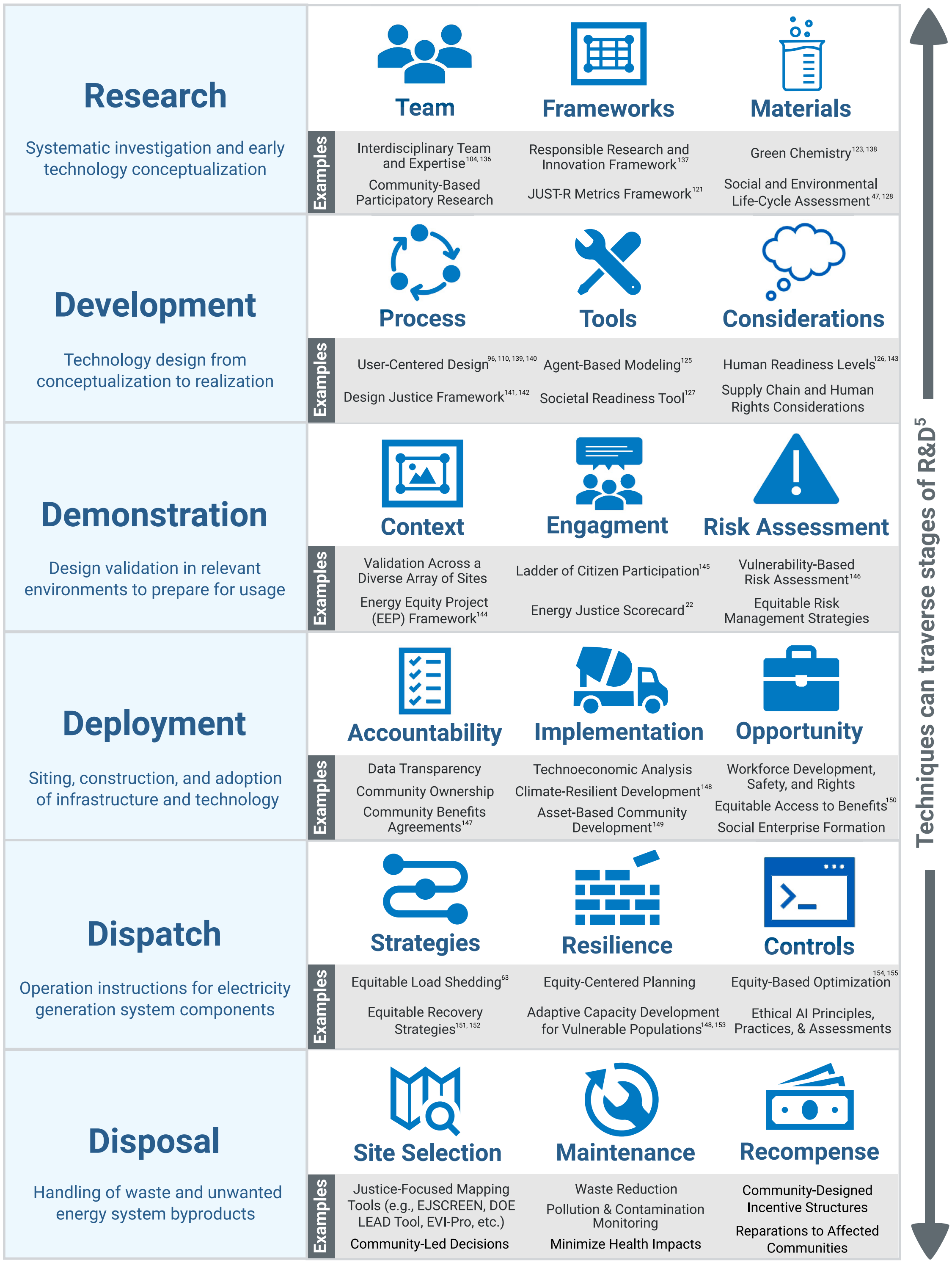

Figure 2. Techniques, tools, and frameworks for incorporating justice in each stage of R&D[5]

Techniques, frameworks, methodologies, and tools that can be applied to incorporate energy justice considerations throughout the R&D[5] continuum. Note these frameworks, techniques, and tools can traverse, and are likely applicable to, many stages of R&D[5]. Community engagement and the centering of frontline communities are particularly important, especially for ensuring a more accurate understanding of the situations these communities face and avoiding brittle decision-making. These elements are either embedded in the techniques displayed here or can be pursued in tandem with them. Example references: Ravikumar

(legend continued on next page)

susceptible to the same failure modes that have led other energy technologies to fall short of their original objectives, take longer than expected, cost more, and cause detrimental harm to the communities they were meant to serve. These failure modalities may be driven by data gaps, community push-back, technology lock-in through path dependencies,[17] brittle decision-making, maladaptation, or poor decision-making under uncertainty. Embedding thoughtful and purposeful consideration of all communities—especially historically vulnerable and marginalized groups and frontline communities—throughout all stages of R&D[5] can aid in mitigating these failure modalities. There is no one framework or method that can be employed to address these failure modalities or to incorporate equity throughout the R&D[5] continuum. Social, economic, technological, and cultural contexts demand a diverse array of tools and perspectives to pursue equitable outcomes. Here, we draw on a number of frameworks and approaches across the literature that can be immediately implemented to integrate equity at various stages of R&D[5], which are summarized in Figure 2 and expounded upon in this paper's supplemental information.

Although the energy transition will be dynamic with myriad unpredictable consequences, if equity and justice remain as important in the future energy system as they have been in the past, we will be well served by more robustly embedding these considerations now before further inequity lock-in. Without incorporating equity, the clean-energy transition is limited. It will be difficult, if not improbable, to achieve a just and sustainable energy transition without a comprehensive embedding of equity principles across all stages of R&D[5]. Researching, designing, developing, and deploying clean-energy technologies with an eye toward justice is a profound reframing of these activities, but such a change in viewpoint better ensures a focus on the transition's ultimate goals from the beginning—a fast, sustainable, and equitable transition to a clean-energy economy for all.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.crsus.2024.100018.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.K.A., W.H., I.F., and K.A.; investigation, B.K.A., W.H., and I.F.; writing – original draft, B.K.A., W.H., and I.F.; writing – review & editing, B.K.A., W.H., I.F., K.F., and K.A.; visualization, B.K.A., W.H., and I.F.; supervision, K.F. and K.A.; project administration, K.A.; funding acquisition, K.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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CRSUS, Volume *1*

Supplemental information

Incorporating energy justice throughout clean-energy R&D[5] in the United States: A review of outcomes and opportunities

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Supplemental Information for "Incorporating energy justice throughout clean-energy R&D[5] in the United States: A review of outcomes and opportunities."

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Table A.1 Publications on failures resulting from equity-myopic approaches to clean energy technology *Disposal*.

N.	Citation	Publication	Topic	Description
1	[9]	Levenda, A. M., Behrsin, I. & Disano, F. (2021). Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. Energy Res. Soc. Sci. 71, 101837	EJ implications of RE	Summarizes documented environmental justice impacts associated with renewable energy technologies. Relevant to Disposal: - *Anaerobic Digestion* | Exposure to human waste; Odor associated with different waste streams - *Biomass* | Exposure to air pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (CO) associated with burning biomass or producing wood pellets - *Hydropower* | Reduced quantity and quality of downstream water, silt formation, and prevent migration of fish; Associated impacts of development including roadbuilding in the region, illegal logging and mining, hydroelectric construction, radioactive dumping, and human rights violations; Local earthquakes, landslides, collapses - *Landfill gas* | Groundwater contamination, odorous gases, exposure to harmful toxicants in landfill gases; pollution associated with transfer stations and truck traffic - *MSW* | Exposure to air pollution produced by waste incineration, including nitrogen oxides, sulfur dioxide, mercury, dioxins and furans; Adverse effects on waste minimization initiatives - *Solar PV* | Waste from PV installations not disposed of properly
2	[29]	Spina, F. Environmental Justice and Patterns of State Inspections. (2015). Soc. Sci. Q. 96, 417–429	Disproportionate environmental inspections	Counties with larger populations of Black residents and counties with higher residential instability, higher population densities, and larger populations of foreign-born residents have disproportionately fewer environmental inspections under federal waste handling laws.
3	[30]	Commission for Racial Justice, United Church of Christ. (1987). Toxic Wastes and Race in the United States: A National Report on the Racial and Socio-Economic Characteristics of Communities with Hazardous Waste Sites. https://www.nrc.gov/docs/ML1310/ML13109A339.pdf.	Disproportionate hazardous waste facility siting	The first national report to comprehensively document the presence of hazardous wastes in racial and ethnic communities throughout the United States. Presents findings from two cross-sectional studies on demographic patterns associated with 1) commercial hazardous waste facilities and 2) uncontrolled toxic waste sites. Race was the most significant predictor of the location of hazardous waste facilities nationwide.
4	[31]	Bullard, R. D., Mohai, P., Saha, R. & Wright, B. (2007). Toxic Wastes and Race at Twenty 1987-2007. https://www.ucc.org/wp-content/uploads/2021/03/toxic-wastes-and-race-at-twenty-1987-2007.pdf	Disproportionate hazardous waste facility siting	Updated report 20 years after the publication of 'Toxic Wastes and Race in the United States'. Uses 2000 Census data, distance-based methods, and a database of commercial hazardous waste facilities to assess the extent of racial and socioeconomic disparities in facility locations. Racial disparities were even greater than previously reported.
5	[32]	Population Surrounding 1,857 Superfund Remedial Sites. https://www.epa.gov/sites/default/files/2015-09/documents/webpopulationrsuperfundsites9.28.15.pdf (2020).	Disproportionate Superfund siting	21 million people in the US live within one mile of a Superfund site. This population is disproportionately minority, low income, linguistically isolated, and less likely to have a high school education than the U.S. population, as a whole.
6	[37]	Amin, R., Nelson, A. & McDougall, S. (2018). A Spatial Study of the Location of Superfund Sites and Associated Cancer Risk. Stat. Public Policy 5, 1–9	Disproportionate Superfund siting and cancer risk	Geographic areas with Superfund sites tend to have elevated cancer risk and elevated proportions of minority populations.

7	[38]	Kiaghadi, A., Rifai, H. S. & Dawson, C. N. (2021). The presence of Superfund sites as a determinant of life expectancy in the United States. Nat. Commun. 12, 1947	Reduced life expectancy from Superfund proximity	The presence of a Superfund site could cause a decrease of -0.186+-0.027 years in life expectancy. This could be as high as -1.22 years in tracts with Superfund sites and high sociodemographic disadvantage.
8	[39]	Currie, J., Greenstone, M. & Moretti, E. (2011). Superfund Cleanups and Infant Health. Am. Econ. Rev. 101, 435–441	Risk of birth defects from Superfund proximity	Uses a differences-in-differences approach to compare birth outcomes before and after a Superfund site clean-up for mothers in proximity of a site. Proximity to a Superfund site before cleanup is associated with a 20-25% increase in the risk of congenital anomalies.
9	[40]	Gómez, J.A. (2021). Superfund EPA: Should Take Additional Actions to Manage Risks from Climate Change Effects, Statement of J. Alfredo Gómez, Director, Natural Resources and Environment, Testimony Before the Subcommittee on Environment and Climate Change, Committee on Energy and Commerce, House of Representatives. In United States. Government Accountability Office (United States. Government Accountability Office).	Superfunds and climate change	60% of Superfund sites may be impacted by natural hazards that will be exacerbated by climate change (including flooding, storm surges, wildfires, and sea level rise) potentially leading to releases of contaminants that could pose even greater risks to the health of the surrounding communities.
10	[41]	U.S. EPA. (2021). End-of-Life Solar Panels: Regulations and Management. U.S. EPA Office of Land and Emergency Management https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management	Hazardous PV waste	Some solar panels contain lead and cadmium which, when present in high enough quantities, can be considered hazardous waste under the EPA's Resource Conservation and Recovery Act (RCRA) at end-of-life disposal.
11	[43]	Weckend, S., Wade, A. & Heath, G. (2016). End of Life Management: Solar Photovoltaic Panels. NREL/TP- 6A20-73852, 1561525 https://www.osti.gov/servlets/purl/1561525/ doi:10.2172/1561525.	PV waste	The International Energy Agency projects that there will be 10 million metric tons of cumulative PV waste in the US and 78 million metric tons worldwide by 2050, leading to an increasing need for end-of-life management approaches including regulations, research into methods of materials recovery, and increasing capabilities for recycling.
12	[44]	Heath, G.A. et al. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy *5*, 502–510. 10.1038/s41560-020-0645-2.	PV waste	Assessment of the global status of practice and knowledge for end-of-life management for crystalline silicon PV modules with a focus on module recycling
13	[45]	Curtis, T., Smith, L., Buchanan, H. & Heath, G. (2021). A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL/TP--6A20-77035, 1768315, MainId:24998 https://www.osti.gov/servlets/purl/1768315/ doi:10.2172/1768315.	Lithium-Ion battery waste	4 million metric tons of lithium-ion electric vehicle batteries will reach the end of their useful life annually by 2040 in the US. Critical materials (cobalt, lithium, nickel, graphite, manganese) are finite and mined in only a few regions of the world, which are often in countries with less-stringent environmental and human health regulations.
14	-	Kumar, A. & Turner, B. (2018). Sociomaterial Solar Waste: Afterlives and Lives After of Small Solar. in Energy Justice Across Borders (Springer Open, 2020).	PV waste from off-grid technologies in the Global South	Connects the literature on off-grid solar for energy access to energy justice concerns about waste using critical postcolonial theories of waste and social ruin.
15	-	Cross, J. & Murray, D. (2018). The afterlives of solar power: Waste	PV waste from off-grid	Tracks the impact of off grid solar products through contexts of breakdown, repair, and disposal. Combines

and repair off the grid in Kenya. Energy Research & Social Science 44, 100–109	technologies in Kenya	stakeholder interviews, a longitudinal survey of product failure rates in Kenya, and ethnographic research at a repair workshop in the town of Bomet. Challenges narratives of energy transitions that fail to address the environmental consequences of mass consumption and present an alternative approach to solar waste embedded in cultures and economies of repair.

Table A.2 Publications on opportunities to incorporate equity and justice considerations in clean energy technology *Disposal*.

N.	Citation	Publication	Topic	Description
1	[44]	Heath, G.A., Silverman, T.J., Kempe, M., Deceglie, M., Ravikumar, D., Remo, T., Cui, H., Sinha, P., Libby, C., Shaw, S., et al. (2020). Research and development priorities for silicon photovoltaic module recycling to support a circular economy. Nat. Energy *5*, 502–510. 10.1038/s41560-020-0645-2.	Circular economy for PV	Assesses the global status of practice and knowledge for end-of-life management for crystalline silicon PV modules. Recommend research and development to reduce recycling costs and environmental impacts compared to disposal while maximizing material recovery.
2	[45]	Curtis, T., Smith, L., Buchanan, H. & Heath, G. (2021) A Circular Economy for Lithium-Ion Batteries Used in Mobile and Stationary Energy Storage: Drivers, Barriers, Enablers, and U.S. Policy Considerations. NREL/TP--6A20-77035, 1768315, MainId:24998 https://www.osti.gov/servlets/purl/1768315/ doi:10.2172/1768315.	Circular economy for batteries	Analyzes drivers, barriers, and enablers to a circular economy for batteries. Projects that 4 million metric tons of lithium-ion electric vehicle batteries will reach the end of their useful life annually by 2040 in the US. Critical materials for batteries (cobalt, lithium, nickel, graphite, manganese) are finite and mined in only a few regions of the world, which are often in countries with less-stringent environmental and human health regulations.
3	[46]	Ahrens, A., Bonde, A., Sun, H., Wittig, N.K., Hammershøj, H.C.D., Batista, G.M.F., Sommerfeldt, A., Frølich, S., Birkedal, H., and Skrydstrup, T. (2023). Catalytic disconnection of C–O bonds in epoxy resins and composites. Nature 617, 730–737. 10.1038/s41586-023-05944-6.	Material recycling technique	Introduces a method for chemically disconnecting carbon-oxygen bonds in the fiber-reinforced thermoset epoxy resins used in aerospace, automotive and wind power industries. The technique recovers polymer building block bisphenol A and fibers from epoxy composites. Researchers demonstrated material recovery on a shell of a wind turbine blade.
4	[48]	Mirletz, H., Ovaitt, S., Sridhar, S. & Barnes, T. M. (2022). Circular economy priorities for photovoltaics in the energy transition. PLOS ONE 17, e0274351	Circular economy for PV	Evaluates two circular economy approaches, lifetime extension and closed-loop recycling, on their ability to reduce virgin material demands and life cycles wastes while meeting capacity goals.

Table B.1 Publications on failures resulting from equity-myopic approaches to clean energy technology *Dispatch*.

N.	Citation	Publication	Topic	Description
1	[9]	Levenda, A. M., Behrsin, I. & Disano, F. (2021). Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. Energy Res. Soc. Sci. 71, 101837	EJ implications of RE	Summarizes documented environmental justice impacts associated with renewable energy technologies. Relevant to Disposal: - *Anaerobic Digestion* | Exposure to human waste; Odor associated with different waste streams - *Biomass* | Exposure to air pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (CO) associated with burning biomass or producing wood pellets - *Hydropower* | Reduced quantity and quality of downstream water, silt formation, and prevent migration of fish; Associated impacts of development including roadbuilding in the region, illegal logging and mining, hydroelectric construction, radioactive dumping, and human rights violations; Local earthquakes, landslides, collapses - *Landfill gas* | Groundwater contamination, odorous gases, exposure to harmful toxicants in landfill gases; pollution associated with transfer stations and truck traffic - *MSW* | Exposure to air pollution produced by waste incineration, including nitrogen oxides, sulfur dioxide, mercury, dioxins and furans; Adverse effects on waste minimization initiatives - *Solar PV* | Waste from PV installations not disposed of properly
2	[51]	Declet-Barreto, J., and Rosenberg, A.A. (2022). Environmental justice and power plant emissions in the Regional Greenhouse Gas Initiative states. PLOS ONE *17*, e0271026. 10.1371/journal.pone.0271026.	GHG emissions reduction disparities	Authors study the ambient air emissions burdens in environmental justice communities from power plants participating in the U.S.'s Regional Greenhouse Gases Initiative. Their findings indicate that power sector carbon mitigation policies that focus on aggregate emissions reductions largely benefitted non-environmental justice communities and had not addressed disparities in pollutant burdens.
3	[55]	Tessum, C.W., Paolella, D.A., Chambliss, S.E., Apte, J.S., Hill, J.D., and Marshall, J.D. (2021). PM2.5 polluters disproportionately and systemically affect people of color in the United States. Sci. Adv. *7*, eabf4491.	Air quality disparities	Study quantifies PM2.5 exposure caused by each emitter type. They show that nearly all major emission categories – from industry and utilities to mobility, residential, and agriculture – contribute to the systemic PM2.5 exposure disparity experienced by people of color. The authors also identify the most inequitable emission source types by state and city to highlight opportunities for addressing the environmental inequity.
4	[59]	Buonocore, J. J., Salimifard, P., Michanowicz, D. R. & Allen, J. G. (2021). A decade of the U.S. energy mix transitioning away from coal: historical reconstruction of the reductions in the public health burden of energy. Environ. Res. Lett. 16, 054030	Mortality from wood and biomass	In 2018 and beyond, the projected mortality impacts of particulate matter-related wood and biomass combustion in energy consuming sectors – residential buildings, commercial buildings, industry, and electricity – are higher than the impacts of coal or gas combustion combined.
5	[60]	Tormos-Aponte, F., García-López, G. & Painter, M. A. (2021). Energy inequality and clientelism in the wake of disasters: From colorblind to affirmative power restoration. Energy Policy 158, 112550	Power restoration inequities	Study on power outage restoration after 2017 hurricane Maria in Puerto Rico. Communities with ties to the ruling party elicited greater government responsiveness while socially vulnerable communities were less likely to be prioritized during disaster relief efforts.

6	[61]	Ferrall, I. Quantitative approaches to energy justice: The theory and praxis of examining fair access to reliable electricity | Chapter 6 Leaving communities of color in the dark: Rotating outages in California create energy and social injustices. (University of California, Berkeley, 2022).	Power outage inequities	Study on rotating outage distribution during extreme heat wave in Northern California. Across different decision-making levels of rotating outage planning and implementation, communities of color were more likely to be at risk of outages that are meant to be ‘short and shared’.
7	[62]	Carvallo, J., Hsu, F. C., Shah, Z. & Taneja, J. (2021). Frozen Out in Texas: Blackouts and Inequity. The Rockefeller Foundation https://www.rockefellerfoundation.org/case-study/frozen-out-in-texas-blackouts-and-inequity/	Power outage inequities	Study on blackouts during winter storm in Texas. Areas with a high share of minority population were more than four times as likely to suffer a blackout than predominantly white areas. Income was not a strong factor.
8	-	Liévanos, R. S. & Horne, C. (2017). Unequal resilience: The duration of electricity outages. Energy Policy 108, 201–211	Power outage inequities	Study on electricity outage durations against census demographics in the American Southwest. Finds that American Indian neighborhoods experience greater disruptions to their electricity supply, but these inequalities are driven more by bureaucratic decision rules (proximity to hospitals, n. downstream customers affected, environmental conditions), than institutional bias.
9	-	Castellanos, S. et al. (2023). A synthesis and review of exacerbated inequities from the February 2021 winter storm (Uri) in Texas and the risks moving forward. Prog. Energy 5, 012003	Power outage inequality impacts	Responses and outcomes of severe winter storm in Feb 2021 in Texas were inconsistent across communities and exacerbated prevailing social and infrastructure inequities.

Table B.2 Publications on opportunities to incorporate equity and justice considerations in clean energy technology *Dispatch*.

N.	Citation	Publication	Topic	Description
1	[52]	Nelson, J. et al. (2012). High-resolution modeling of the western North American power system demonstrates low-cost and low-carbon futures. Energy Policy 43, 436–447.	Carbon price	Adding a carbon price to least-cost capacity expansion modeling in North America induces changes to the optimal technology deployment types, timing, and capacity installed, in addition to dispatch patterns. As the carbon price rises, coal is replaced with solar, wind, gas, and/or nuclear expansion.
2	[57]	Ravi, V., Li, Y., Heath, G., Marroquin, I., Day, M., and Walzberg, J. (2023). LA100 Equity Strategies. Chapter 11: Truck Electrification for Improved Air Quality and Health 10.2172/2221835.	Equitable truck decarbonization strategies	Chapter of the NREL-led LA100 Equity Strategies report focuses on truck decarbonization. Along with community guidance, researchers analyzed emissions from heavy-duty trucks to identify the impacts of truck decarbonization on communities and make recommendations for the city of Los Angeles based on findings.
3	[58]	Kerl, P. Y. et al. (2015). New approach for optimal electricity planning and dispatching with hourly time-scale air quality and health considerations. Proc. Natl. Acad. Sci. 112, 10884–10889.	Health externalities	Integrated an air pollutant atmospheric model into an electricity production model to study health impacts by shifting production. Find that incorporating health externalities into power plant operation in the state of Georgia provides a net savings of $13 million USD/year between health savings and generation costs.
4	[63]	Kody, A., West, A., and Molzahn, D.K. (2022). Sharing the load: Considering fairness in de-energization scheduling to mitigate wildfire ignition risk using rolling optimization. In 2022 IEEE 61st Conference on Decision and Control (CDC) (IEEE), pp. 5705–5712.	Optimization for fairer load shedding	Presents a framework for selecting lines to de-energize during public safety power shut-off events used to mitigate wildfire risks. Framework is developed to balance wildfire risk reduction, total load shedding, and fairness considerations and tested using California demand data and wildfire risk forecasts. Results demonstrate that the proposed formulation can provide more fair outcomes with limited impacts on system-wide performance.
5	[64]	Clark, S. S., Peterson, S. K. E., Shelly, M. A. & Jeffers, R. F. (2023). Developing an equity-focused metric for quantifying the social burden of infrastructure disruptions. Sustain. Resilient Infrastruct. 8, 356–369	Social burden of infrastructure disruptions	Presents a novel, theoretically-grounded framework to quantify the social burden of infrastructure disruptions. Utilizing a Capabilities Approach theory to human development, their metric focuses on "estimating the burden of post-event adaptations taken by households to maintain their basic capabilities (e.g., ability to access food and water) and fulfill important household functionings (e.g., maintaining health and well-being)."
6	[65]	Cong, S., Nock, D., Qiu, Y.L., and Xing, B. (2022). Unveiling hidden energy poverty using the energy equity gap. Nat. Commun. *13*, 2456. 10.1038/s41467-022-30146-5.	Energy-limiting behaviors in low-income households	Study investigates energy-limiting behavior (i.e., those without comfortable indoor temperatures) in low-income households using a residential electricity consumption dataset. They find a gap in the frequently used income-based energy burden metric, which has a 10% energy expenditure to income threshold. Authors introduce a relative energy poverty metric – the energy equity gap – defined as the difference in the inflection temperatures between low and high-income groups.
7	[66]	Dargin, J.S., and Mostafavi, A. (2020). Human-centric infrastructure resilience: Uncovering well-being risk disparity due to infrastructure disruptions in disasters. PLOS ONE *15*, e0234381. 10.1371/journal.pone.0234381.	Effects of service disruptions on well-being	This paper examines the impacts of infrastructure service disruptions on the well-being of vulnerable populations during disasters. Authors also derive an empirical relationship between household sociodemographic factors and well-being impacts due to disruptions in various infrastructure services – such as transportation, food, communications, and water – during and immediately after Hurricane Harvey.
8	[151]	Lee, C.-C., Maron, M., and Mostafavi, A. (2022). Community-scale big data reveals disparate impacts of the Texas winter storm of 2021 and its managed power outage. Humanit. Soc. Sci. Commun. 9, 1–12.	Analysis of community burdens from disruptions	Researchers use aggregated community-scale data to provide insights into the disparate impacts of managed power outages, burst pipes, and food inaccessibility during extreme weather events. Results highlight spatial and temporal impacts on vulnerable subpopulations in Harris County, TX and inequality in the management and

				implementation of power outages. Insights from this type of analysis can form a basis from which infrastructure operators might enhance social equality during managed service disruptions.
9	[152]	Lin, Y., Wang, J., and Yue, M. (2022). Equity-based grid resilience: How do we get there? Electr. J. 35, 107135. 10.1016/j.tej.2022.107135.	Equity-focused grid resilience techniques	Review of the implications of equity in the power system, the significance of guaranteeing energy equity both in everyday operation and disaster management, and the ongoing efforts to plan for equable. Authors propose a holistic power grid resilience enhancement framework that covers different stages of disaster management and dimensions of energy equity.
10	[153]	Kim, Y., Smith, J.B., Mack, C., Cook, J., Furlow, J., Njinga, J.-L., and Cote, M. (2017). A perspective on climate-resilient development and national adaptation planning based on USAID’s experience. Clim. Dev. 9, 141–151. 10.1080/17565529.2015.1124037.	Climate-resilient development	Introduces the United States Agency for International Development's (USAID's) Climate-Resilient Development framework, which employs a “development-first” approach, rather than a “climate-first” or climate stressor-driven approach to enable more effective integration of climate mitigation into development planning and decision-making. Presents lessons learned from applying this approach in stakeholder workshops in Jamaica, West Africa, and Tanzania.
11	[154]	Heleno, M., Sigrin, B., Popovich, N., Heeter, J., Jain Figueroa, A., Reiner, M., and Reames, T. (2022). Optimizing equity in energy policy interventions: A quantitative decision-support framework for energy justice. Appl. Energy 325, 119771. 10.1016/j.apenergy.2022.119771.	Equity optimization in energy policy decision-making	Presents a quantitative decision-making framework to support policy decision-making around equitable energy interventions. Framework enables identification of optimal energy interventions to decrease energy insecurity and combines technoeconomic energy planning with tract-level sociodemographic data.
12	[155]	Syal, S.M. (2022). Embedding Human Perspective and Equity in the Design of Sustainable Energy and Transportation Systems. ProQuest Diss. Theses.	Human-centered design and equity in energy and transportation	Explores ways to embed human needs and equity into sustainable energy and transportation systems modeling efforts. Presents methods for integrating human perspective in wind and solar models and introduces a holistic approach to integrating human perspective in sociotechnical models with a focus on equity. Also studies how to transition to a decarbonized transportation sector in a way that is inclusive and empowers communities, with a case study in Sonoma County, CA.
13	-	Castellanos, S. et al. (2023). A synthesis and review of exacerbated inequities from the February 2021 winter storm (Uri) in Texas and the risks moving forward. Prog. Energy 5, 012003	Opportunities for equitable long-term infrastructure planning	Documents opportunities for equitable long-term infrastructure planning and recovery across the electricity sector, water systems, housing and living conditions, road transportation, and communication systems and practices.

Table C.1 Publications on failures resulting from equity-myopic approaches to clean energy technology *Deployment*.

N.	Citation	Publication	Topic	Description
1	[9]	Levenda, A. M., Behrsin, I. & Disano, F. (2021). Renewable energy for whom? A global systematic review of the environmental justice implications of renewable energy technologies. Energy Res. Soc. Sci. 71, 101837	EJ implications of RE	Summarizes documented environmental justice impacts associated with renewable energy technologies. Relevant to Disposal: - *Anaerobic Digestion* | Exposure to human waste; Odor associated with different waste streams - *Biomass* | Exposure to air pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and carbon monoxide (CO) associated with burning biomass or producing wood pellets - *Hydropower* | Reduced quantity and quality of downstream water, silt formation, and prevent migration of fish; Associated impacts of development including roadbuilding in the region, illegal logging and mining, hydroelectric construction, radioactive dumping, and human rights violations; Local earthquakes, landslides, collapses - *Landfill gas* | Groundwater contamination, odorous gases, exposure to harmful toxicants in landfill gases; pollution associated with transfer stations and truck traffic - *MSW* | Exposure to air pollution produced by waste incineration, including nitrogen oxides, sulfur dioxide, mercury, dioxins and furans; Adverse effects on waste minimization initiatives - *Solar PV* | Waste from PV installations not disposed of properly
2	[10]	Baker, S. H. (2018). Emerging challenges in the global energy transition: a view from the frontlines. Energy Justice 232–257	Wind displacing indigenous communities	Examines how indigenous communities in Mexico are being impacted by renewable energy investments by private capital from the Global North, sparked by Mexico's market-oriented transition.
3	[11]	Sunter, D. A., Castellanos, S. & Kammen, D. M. (2019). Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. Nat. Sustain. 2, 71–76	Disparities in rooftop PV adoption	Compares the relative adoption of rooftop PV across census tracts grouped by racial and ethnic majority. Black- and Hispanic-majority census tracts showed significantly less rooftop solar PV installed even after accounting for differences in income and home ownership.
4	[12]	Hernández, D. (2015). Sacrifice Along the Energy Continuum: A Call for Energy Justice. Environ. Justice 8, 151–156. 10.1089/env.2015.0015.	Injustice along the energy continuum	Discusses ways in which energy supply- and demand-side dynamics affect vulnerable communities along the spectrum of energy production and consumption through burdens from energy sacrifice zones and other energy injustices. The article seeks to lay a foundation for examining critical sacrifices along the energy continuum and proposes four basic rights for vulnerable communities to enhance recognition and equity in the energy sector: (1) the right to healthy, sustainable energy production; (2) the right to best available energy infrastructure; (3) the right to affordable energy; and (4) the right to uninterrupted energy service.
5	[26]	Newell, P.J., Geels, F.W., and Sovacool, B.K. (2022). Navigating tensions between rapid and just low-carbon transitions. Environ. Res. Lett. *17*, 041006. 10.1088/1748-9326/ac622a.	Tensions between equitable and incumbent approaches	Discuss barriers and tensions that arise between rapid, large-scale decarbonization and pursuing procedural justice in the energy transition given existing power and resource structures. They highlight a need for greater clarity around when citizen engagement works well and discuss instances in which a lack of meaningful commitments to communities delayed progress. They also discuss how incumbent firms have technical, financial, and organizational resources to deploy technologies more quickly and at larger scales than grassroots innovators although incumbent firms have not historically prioritized energy justice.

6	[69]	Brockway, A. M., Conde, J. & Callaway, D. (2021). Inequitable access to distributed energy resources due to grid infrastructure limits in California. Nat. Energy 6, 892–903.	Disparities in grid hosting capacity for DERs	Analyzed grid limits to new DER integration across California's two largest utility territories. Found that grid limits reduce access to solar photovoltaics to less than half of the households served by these two utilities, which may hinder California's electric vehicle adoption and residential load electrification goals. These grid limits further exacerbate inequalities for Black-identifying and disadvantaged census block groups who have disproportionately less access to new solar PV capacity based on circuit hosting capacity.
7	[70]	Cushing, L.J., Li, S., Steiger, B.B., and Casey, J.A. (2023). Historical red-lining is associated with fossil fuel power plant siting and present-day inequalities in air pollutant emissions. Nat. Energy *8*, 52–61. 10.1038/s41560-022-01162-y.	Red-lining and fossil fuel plant siting	Study assesses whether racialized appraisals of investment risk ('red-lining') undertaken by the US federal Home Owners' Loan Corporation in the 1930s influenced the subsequent siting of fossil fuel power plants. Results show that neighborhoods deemed 'hazardous' (D grade, 'red-lined') had a higher likelihood of a fossil fuel power plant being sited between 1940 and 1969 (72%), 1970 and 1999 (20%) and 2000 and 2019 (31%), and higher average present-day emissions of nitrous oxides (82%), sulfur dioxide (38%) and fine particulate matter (63%) compared with 'declining' (C-graded) neighbourhoods. These findings suggest racism in the housing market contributed to inequalities in present-day power plant emissions burdens.
8	[71]	Nelson, R.K. and Ayers, E.L. Digital Scholarship Lab Renewing Inequality. https://dsl.richmond.edu/panorama/renewal/#view=0/0/1&viz=cartogram.	Visualizations of urban renewals displacements	Visualizations show the number of families that cities reported displacing through federally-funded urban renewal programs between 1955 and 1966. The urban renewal projects that resulted in displacements were typically aimed at "slum clearance": using eminent domain to acquire private homes that were usually deemed sub-standard, razing those houses, and redeveloping the land for new, sometimes public housing, more often private, or for other purposes like the development of department stores or office buildings. The visualization also shows how displacements had a much bigger effect upon communities of color.
9	[79]	Sovacool, B. K. et al. (2022). Conflicted transitions: Exploring the actors, tactics, and outcomes of social opposition against energy infrastructure. Glob. Environ. Change 73, 102473.	Opposition to energy infrastructure	Systematically explores recent opposition to a range of energy infrastructures across 130 cases in Asia, Europe, and North America. Details the configurations of types of infrastructure (transmission, wind, solar, hydro, oil, gas, coal, pipelines, nuclear, quarries), actors, tactics (meetings, litigation, protests, petitions, independent assessment, suppression, not-in-my-backyard), and outcomes (remuneration, policy change, concessions, labor protections).
10	[80]	Nordholm, A. & Sareen, S. (2021).Scalar Containment of Energy Justice and Its Democratic Discontents: Solar Power and Energy Poverty Alleviation. Front. Sustain. Cities 3.	Scale of PV affects justice outcomes	Multi-scalar analysis of solar PV rollout in Lisbon, Portugal. The scale used in the analysis and execution of energy operations and transitions matters for justice outcomes. Smaller scale solar PV offers opportunities for increased energy democracy, however it has offered limited opportunities for participation from energy poor households. A country-wide building renovation strategy contained prohibitively large procedural and technical hurdles, effectively limiting this subsidy to well-educated and wealthy households.
11	[118]	Diffenbaugh, N. S. & Burke, M. (2019). Global warming has increased global economic inequality. Proceedings of the National Academy of Sciences **116**, 9808–9813.	Unequal impacts of climate change	Authors find that global warming has very likely exacerbated global economic inequality, including ~25% increase in population-weighted between-country inequality over the past half century.
12	[119]	US EPA. (2021). *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts.*	Unequal impacts of climate change	This report improves our understanding of the degree to which four socially vulnerable populations – defined based on income, educational attainment, race and

		https://www.epa.gov/cira/social-vulnerability-report		ethnicity, and age – may be more exposed to the adverse impacts of climate change.
13	[134]	Partridge, T., Thomas, M., Pidgeon, N. & Harthorn, B. H. (2018). Urgency in energy justice: Contestation and time in prospective shale extraction in the United States and United Kingdom. Energy Res. Soc. Sci. 42, 138–146	Discourse of urgency	Focuses on public view on prospective shale oil and gas extraction in the United States and the United Kingdom. Proposes urgency as a pivotal concept in researching i) the justice and socioenvironmental implications of energy systems and technological change and ii) in understanding how people make sense of contested energy timeframes. Urgency discourses including 'quick fix' solutions viewed critically and encountered resistance. Urgency tends to reinforce the status quo, effectively perpetuating extant social barriers and exacerbating rather than reducing socio-economic inequalities.

Table C.2 Publications on opportunities to incorporate equity and justice considerations in clean energy technology *Deployment*.

N.	Citation	Publication	Topic	Description
1	[73]	Roddis, P., Carver, S., Dallimer, M., Norman, P. & Ziv, G. (2018). The role of community acceptance in planning outcomes for onshore wind and solar farms: An energy justice analysis. Appl. Energy 226, 353–364.	Factors driving community acceptance of solar/wind	Analyses the effect of community acceptance on planning application outcomes for onshore wind and solar farms in Great Britain between 1990 and 2017. Different factors influence community acceptance of each technology and their respective planning decision-making processes, although visibility, installed capacity, social deprivation, and year of planning application were found in common
2	[74]	Boudet, H. S. (2019). Public perceptions of and responses to new energy technologies. Nat. Energy 4, 446–455.	Understanding perceptions of new technologies	Reviews the literature on public perceptions of and responses to a wide range of new energy technologies. Identifies four factors - technology, people, place, process. Given recent trends, people and place factors will play outsized roles in shaping public perceptions of new energy technologies in the future. Understanding and adapting technologies and decision-making processes to a particular place and people will become increasingly important for the successful deployment of new energy technologies.
3	[75]	Sareen, S. & Haarstad, H. (2018). Bridging socio-technical and justice aspects of sustainable energy transitions. Appl. Energy 228, 624–632.	Bridging socio-technical and justice in transitions	A comprehensive approach [that pulls together socio-technical development and energy justice in understanding sustainable transitions] requires analyses to account for the co-evolution of *institutional* change, *material* change, and *relational* change, with a cross-cutting concern for multiple spatialities and normative implications. Case study on multi-scalar solar uptake in Portugal.
4	[76]	Bidwell, D. (2013). The role of values in public beliefs and attitudes towards commercial wind energy. Energy Policy 58, 189–199.	Understanding attitudes towards wind	Studies the role of values in public beliefs and attitudes towards commercial wind energy in Michigan. Finds that the values underlying support towards wind energy development are related to a broader concern for community and beyond (altruism). The role of values lends support for more participatory development processes.
5	[77]	Mundaca, L., Busch, H. & Schwer, S. (2018). 'Successful' low-carbon energy transitions at the community level? An energy justice perspective. Appl. Energy 218, 292–303.	Examining EJ in two European energy transitions	Critically analyzes so-called 'successful' low-carbon energy transitions (Denmark and Germany) using energy justice. Examines the consultation processes, information flow/sharing, decision-making, and outcomes. Evidence of perceived procedural justice was found due to local, bottom-up, intensive information and consultation processes. Perceived energy justice was more positive if social and environmental outcomes were considered, including compensation schemes. Perceived fairness of procedures was a critical pre-condition for the perceived legitimacy of outcomes.
6	[78]	Ottinger, G., Hargrave, T. J. & Hopson, E. (2014). Procedural justice in wind facility siting: Recommendations for state-led siting processes. Energy Policy 65, 662–669.	State-led wind siting	Proposes a collaborative governance approach to wind facility siting in which state governments retain ultimate authority over permitting decisions but encourage and support local-level deliberations as the primary means of making those decisions.
7	[81]	Enserink, M., Van Etteger, R., Van den Brink, A. & Stremke, S. (2022). To support or oppose renewable energy projects? A systematic literature review on the factors influencing landscape design and social acceptance. Energy Res. Soc. Sci. 91, 102740.	Factors influencing RE acceptance	Reviews and compares research from 'designing landscape transformations' and 'acceptance of renewable energy projects' in terms of how they describe the local acceptance of renewable energy projects. The two literatures describe 25 similar factors (economic benefits, visual impact, aesthetics, scenic quality). Acceptance studies had 45 unique factors (trust), and landscape studies had 16 unique factors (community involvement & participation),

				with different distributions. Emphasis in peer-reviewed literature differs from that of laypersons (environmental over process).
8	[124]	Syal, S. M., Ding, Y. & MacDonald, E. F. (2020). Agent-Based Modeling of Decisions and Developer Actions in Wind Farm Landowner Contract Acceptance. J. Mech. Des. 142.	Wind Farm Landowner Contract Acceptance	Presents an agent-based model to investigate interactions between wind farm developers and landowners, particularly during the landowner acquisition period. Uses past studies to quantify three actions a developer can take to influence landowners: (1) community engagement meetings, (2) preliminary environmental studies, and (3) sharing the wind turbine layout with the landowner. Results show how landowner acceptance rates can change over time based on what actions the developer takes.
9	[139]	Aziz, M. J. et al. (2022). A co-design framework for wind energy integrated with storage. Joule 6, 1995–2015.	Co-design for wind and storage	Proposes a co-design approach that considers wind energy combined with storage from a full social, technical, economic, and political viewpoint. To address the coupled inter-related challenges of cost, technology readiness, system integration, and societal considerations of acceptance, adoption, and equity.
10	[147]	DOE Office of Economic Impact and Diversity Community Benefit Agreement (CBA) Toolkit. Energy.gov. https://www.energy.gov/diversity/community-benefit-agreement-cba-toolkit.	Community benefit agreement	Resources offered by the U.S. Department of Energy's Office of Economic Impact and Diversity for pursuing Community Benefit Agreements
11	[148]	Schipper, E.L.F. et al. (2022). Climate resilient development pathways climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II Sixth Assess. Rep. Intergov. Panel O N Clim. Change Issue.	Climate resilient development	Extensive resource from the Intergovernmental Panel on Climate Change on climate resilient development strategies and potential outcomes.
12	[149]	Mathie, A., and Cunningham, G. (2003). From clients to citizens: Asset-based community development as a strategy for community-driven development. Dev. Pract. 13, 474–486.	Asset-based community development	This article introduces asset-based community development, its principles, and relevant practices.
13	[150]	Farley, C., Howat, J., Bosco, J., Thakar, N., Wise, J., and Su, J. (2021). Advancing Equity in Utility Regulation (Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States)).	Equity in utility regulation	Introduces energy equity in the context of energy utilities. Analyzes the need for equity in energy utility regulation and provides recommendations for utility regulators.
14	-	Huijts, N. M. A., Molin, E. J. E. & Steg, L. (2012). Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. Renew. Sustain. Energy Rev. 16, 525–531.	Factors influencing RE acceptance	Proposes comprehensive framework of energy technology acceptance based on a review of psychological theories and empirical studies. Attitudes are influenced by perceived costs, risks and benefits, positive and negative feelings in response to the technology, trust, procedural fairness, and distributive fairness. Personal norm is influenced by perceived costs, risks and benefits, outcome efficacy, and awareness of adverse consequences of not accepting the new technology.
15	-	Wolsink, M. (2007). Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. Renew. Sustain. Energy Rev. 11, 1188–1207.	Wind power acceptance	Early paper on understanding perceptions and public attitudes towards wind power. The success of wind power depends on the inclusion of the local public in decision-making through a participatory, collaborative approach. Consultation after a plan (location) has been announced is more of a trigger for opposition than an incentive for the proper design of acceptable projects.

16	-	Walker, C. & Baxter, J. (2017). Procedural justice in Canadian wind energy development: A comparison of community-based and technocratic siting processes. Energy Research & Social Science 29, 160–169.	Resident perceptions of procedural justice in wind farm siting	Mixed methods study to explore differences in the ways governments and developers enact wind energy development planning and how this impacts acceptance/support and procedural justice outcomes in two Canadian provinces. Found stronger perceived procedural justice in the province which anchored its development strategy more explicitly with a community-based program. In the other province, opposition to local developments was highly conflated with a lack of procedural justice including few opportunities to take part in siting.
17	-	Ross, E., Day, M., Ivanova, C., McLeod, A. & Lockshin, J. (2022). Intersections of disadvantaged communities and renewable energy potential: Data set and analysis to inform equitable investment prioritization in the United States. Renewable Energy Focus 41, 1–14.	Renewable energy potential dataset	Creates a dataset of renewable energy development potential across US counties. Identifies where disadvantaged community indicators and high generation potential from cost-effective renewable energy intersect and deployment could lead to economic development and job creation.
18	-	Spurlock, C.A., Elmallah, S., and Reames, T.G. (2022). Equitable deep decarbonization: A framework to facilitate energy justice-based multidisciplinary modeling. Energy Research & Social Science *92*, 102808. 10.1016/j.erss.2022.102808.	Equity-based decarbonization framework	Introduces the Equitable Deep Decarbonization Framework for mapping tenets of restorative, recognition, procedural, and distributive energy justice to modeling large-scale, deep decarbonization pathways to facilitate multidisciplinary effort. Authors present key considerations for each step of the framework to enable modeling that accounts for adaptation co-benefits associated with systematic climate risks to vulnerable communities.

Table D.1 Publications on failures resulting from equity-myopic approaches to clean energy technology *Development and Demonstration*.

N.	Citation	Publication	Topic	Description
1	[90]	Hossain, Y., Loring, P. A. & Marsik, T. (2016). Defining energy security in the rural North—Historical and contemporary perspectives from Alaska. Energy Res. Soc. Sci. 16, 89–97.	Household energy security in Alaska	Illustrates historical and contemporary, place-based contours of household energy security for rural and indigenous Alaskans. Redefines energy security for households rather than for countries. Documents the forced replacement of traditional Alaska Native homes with poorly insulated, fossil fuel- and imported lumber-dependent, Euro-American wood frame houses.
2	[92]	Barnes, D. F., Openshaw, K., Smith, K. R. & Plas, R. van der. (1994). What Makes People Cook with Improved Biomass Stoves? A Comparative International Review of Stove Programs. 60 https://documents1.worldbank.org/curated/en/738011468766789505/pdf/multi-page.pdf	Cookstove adoption	Many levels of energy sector restructuring has shown that enduring change cannot be achieved solely by technological means. This comprehensive review of the successes and failures of stove programs provides a case in point: no matter how efficient or cheap the stove, individual households have proved reluctant to adopt it if it is difficult to install and maintain or less convenient and less adaptable to local preferences than its traditional counterpart.
3	[93]	Ruiz-Mercado, I., Masera, O., Zamora, H. & Smith, K. R. (2011). Adoption and sustained use of improved cookstoves. Energy Policy 39, 7557–7566.	Cookstove adoption	Providing access to improved cookstoves is necessary but not sufficient to achieve any of the goals of stove programs. Sustained use is critical to ensure the sustainability of cookstove benefits. The introduction of new fuel/devices is a dynamic process with strong interactions with users and the larger socioeconomic and ecological context. More than switching to new cookstoves people stack devices and fuels based on the preferred combinations for the main cooking tasks.
4	-	Behrsin, I. (2020). Controversies of justice, scale, and siting: The uneven discourse of renewability in Austrian waste-to-energy development. Energy Research & Social Science 59, 101252.	Waste-to-energy discourse	Planning and management discourse around waste incineration in Europe often considers the technology to be green, renewable, and carbon-neutral, which obscures environmental justice groups contestations that considering it renewable exacerbates air quality issues for overburdened communities.

Table D.2 Publications on opportunities to incorporate equity and justice considerations in clean energy technology *Development and Demonstration*.

N.	Citation	Publication	Topic	Description
1	[22]	Baker, S., DeVar, S., and Parkash, S. (2019). The Energy Justice Workbook (Initiative for Energy Justice).	Energy justice introduction and assessment	Accessible guide that introduces energy justice, energy equity, and key principles. Provides a workbook, metrics, and an energy justice scorecard for others to apply, along with policy case study examples.
2	[47]	Norgren, A., Carpenter, A. & Heath, G. (2020). Design for Recycling Principles Applicable to Selected Clean Energy Technologies: Crystalline-Silicon Photovoltaic Modules, Electric Vehicle Batteries, and Wind Turbine Blades. J. Sustain. Metall. 6, 761–774	Design for recycling, multi-technology	Synthesizes design for recycling principles and applies them to crystalline-silicon PV modules, batteries for electric vehicles, and wind turbine blades.
3	[82]	Martin, A., Agnoletti, M.-F. & Brangier, E. (2020). Users in the design of Hydrogen Energy Systems: A systematic review. Int. J. Hydrog. Energy 45, 11889–11900	Hydrogen Energy System adoption	Reviews 152 publications on hydrogen energy system (HES) end users, identifying approaches implemented to take users into account. Results indicate that final users are mostly perceived as a barrier to the deployment of HES, or as a parameter to be assessed rather than as a resource for the design. Recommends focusing studies on upstream user research aimed at stimulating and enhancing technologies and systems design.
4	[84]	Bao, Q., Sinitskaya, E., Gomez, K. J., MacDonald, E. F. & Yang, M. C. (2020). A human-centered design approach to evaluating factors in residential solar PV adoption: A survey of homeowners in California and Massachusetts. Renewable Energy 151, 503–513	HCD to residential PV adoption	Interviewed 18 solar stakeholders and conducted 1,773 homeowner surveys of solar adopters and non-adopters in California and Massachusetts. Cost savings, solar system reliability, installer warranty, and reviewer ratings of the installer were the most important factors when these homeowners considered purchasing a solar system. Solar owners ranked reliability as even more important than price. These findings can inform designers, engineers, and manufacturers as they create more compelling residential PV systems.
5	[88]	van de Poel, I. (2009). Values in Engineering Design. In Philosophy of Technology and Engineering Sciences Handbook of the Philosophy of Science., A. Meijers, ed. (North-Holland), pp. 973–1006. 10.1016/B978-0-444-51667-1.50040-9.	Value-sensitive design	Explores the role of values in engineering design and introduces techniques to elucidate, translate, and embed values in engineering design activities, choices, and across the engineering design process.
6	[91]	Abras, C., Maloney-Krichmar, D., and Preece, J. (2004). User-centered design. Bainbridge W Encycl. Hum.-Comput. Interact. Thousand Oaks Sage Publ. *37*, 445–456.	User-centered design	Presents history of and introduction to design concepts such as user-centered design (USD) and participatory design, along with techniques to apply these methods.
7	[92]	Barnes, D. F., Openshaw, K., Smith, K. R. & Plas, R. van der. (1994). What Makes People Cook with Improved Biomass Stoves? A Comparative International Review of Stove Programs. https://documents1.worldbank.org/curated/en/738011468766789505/pdf/multi-page.pdf	Cookstove adoption	In addition to D1: Households have been most receptive when the cookstove dissemination process takes full account of the capacities and needs of local stove producers and consumers. Technical improvements in cookstove efficiency must be complemented by appropriate project design and implementation, perceptibly superior services, and proper institutional support, if they are truly to take root.
8	[94]	Gill-Wiehl, A. & Kammen, D. M. (2022). A pro-health cookstove strategy to advance energy, social and ecological justice. Nat.	Pro-health cookstove strategies	Challenges the fuel-neutral positions of prominent multi-lateral institutions funding cookstove development efforts by promoting a pro-health strategy in which the stoves promoted meet the

		Energy 1–4 doi:10.1038/s41560-022-01126-2.		World Health Organization's Health Tiers 4 or 5. Further, this pro-health strategy does not conflict with climate goals - all stoves and fuels above Tier 4 provide emissions reductions.
9	[95]	Bødker, S., Dindler, C., Iversen, O. S. & Smith, R. C. (2022). What Are the Results of Participatory Design? in Participatory Design (eds. Bødker, S., Dindler, C., Iversen, O. S. & Smith, R. C.) 95–102 (Springer International Publishing, 2022). doi:10.1007/978-3-031-02235-7_9.	Participatory design research	Although Participatory Design has been (and still is) particularly concerned with technology, the outcomes of Participatory Design go beyond useful technological products. They may involve organizational change, new practices, insights, learning, or other kinds of effects that reach beyond technology. Moreover, they reflect the four strong commitments in Participatory Design to democracy, empowerment, mutual learning, and skillfulness.
10	[96]	McGookin, C., Ó Gallachóir, B., and Byrne, E. (2021). Participatory methods in energy system modelling and planning – A review. Renew. Sustain. Energy Rev. 151, 111504. 10.1016/j.rser.2021.111504.	Participatory energy system modeling	Reviews of participatory methods in energy system modeling and planning. Authors describe the key benefits and challenges of pursing a participatory approach in energy modeling and planning efforts along with emerging research directions in this space.
11	[97]	Edmunds, D.S., Shelby, R., James, A., Steele, L., Baker, M., Perez, Y.V., and TallBear, K. (2013). Tribal Housing, Codesign, and Cultural Sovereignty. Sci. Technol. Hum. Values 38, 801–828.	Tribal housing design	Assesses a collaboration between the University of California, Berkeley's Community Assessment of Renewable Energy and Sustainability program and the Pinoleville Pomo Nation, a small Native American tribal nation in northern California. The collaboration focused on creating culturally inspired, environmentally sustainable housing for tribal citizens using a codesign methodology developed at the university. The housing design process is evaluated in terms of both its contribution to Native American "cultural sovereignty," as elaborated by Coffey and Tsosie, and as a potential example of the democratization of scientific practice.
12	[99]	Stein, P.J.S., Stein, M.A., Groce, N., and Kett, M. (2023). The role of the scientific community in strengthening disability-inclusive climate resilience. Nat. Clim. Change 13, 108–109. 10.1038/s41558-022-01564-6.	Disability-inclusive climate resilience	Comment that discusses how the scientific community could advance and hasten the development of disability-inclusive climate resilience, and which areas should be prioritized.
13	[100]	Viswanathan, M. et al. (2004). Community-based participatory research: Assessing the evidence: Summary. AHRQ Evid. Rep. Summ.	Community-based participatory research	Review that defines community-based participatory research (CBPR), its implementation, and efficacy. CBPR found to involve co-learning and reciprocal transfer of expertise, shared decision-making power, and mutual ownership of the process and products of the research enterprise. Documented outcomes of CBPR included improved research quality, increased community, and research capacity, and stronger or more consistent positive health outcomes.
14	[101]	Wallerstein, N. et al. (2020). Engage for Equity: A Long-Term Study of Community-Based Participatory Research and Community-Engaged Research Practices and Outcomes. Health Educ. Behav. 47, 380–390	Community-based participatory research	Identifies which community-based participatory research partnering practices, under which contexts and conditions, have the capacity to contribute to health, research, and community outcomes using learned lessons from their Engage for Equity grant.
15	[120]	Dombrowski, L., Harmon, E. & Fox, S. (2016). Social justice-oriented interaction design: Outlining key design strategies and commitments. in Proceedings of the 2016 ACM Conference on Designing Interactive Systems 656–671	Social justice-oriented design	Develops a social justice orientation to designing for 'wicked' problems. Highlight design strategies that target the goals of social justice along six dimensions – transformation, recognition, reciprocity, enablement, distribution, and accountability – and elaborates on three commitments necessary to developing a social justice-oriented design practice: a commitment to

				conflict, a commitment to reflexivity, and a commitment to personal ethics and politics.
16	[125]	Mabey, C.S., Armstrong, A.G., Mattson, C.A., Salmon, J.L., Hatch, N.W., and Dahlin, E.C. (2021). A computational simulation-based framework for estimating potential product impact during product design. Des. Sci. 7, e15. 10.1017/dsj.2021.16.	Estimating product impacts	Provides a framework for estimating product impact during product design by integrating models of the product, scenario, society and impact using agent-based modeling. Although the framework is demonstrated using only social impact, authors claim the framework can also be applied to economic or environmental impacts individually or concurrently.
17	[140]	van de Poel, I. (2013). Translating Values into Design Requirements. In Philosophy and Engineering: Reflections on Practice, Principles and Process, D. P. Michelfelder, N. McCarthy, and D. E. Goldberg, eds. (Springer Netherlands), pp. 253–266.	Value-Sensitive Design	Introduces a method to translate values into design requirements through a hierarchical structure of values, norms, and requirements. The author also presents examples of use of this values translation methodology.
18	[141]	Costanza-Chock, S. (2020). Design Justice: Community-Led Practices to Build the Worlds We Need (The MIT Press).	Design justice	Discusses the relationship among design, power, and social justice. Introduces design justice as an approach to design that is led by marginalized communities and that aims explicitly to challenge, rather than reproduce, structural inequalities. Explores theory and practice of design justice
19	[142]	Das, M., Roeder, G., Ostrowski, A.K., Yang, M.C., and Verma, A. (2023). What Do We Mean When We Write About Ethics, Equity, and Justice in Engineering Design? J. Mech. Des. 145, 061402.	Ethics, equity, and justice in engineering design	Review of three leading engineering design journals to investigate how, when, and why ethics, equity, and justice, and their variations appear in the engineering design literature and what scholars mean when they use them. Authors propose an expanded design justice framework that is specific to engineering design and encourage designers to adopt the framework to assist them in thinking through how their engineering design work can be used to advance justice.
20	[143]	Phillips, E.L. (2010). The development and initial evaluation of the human readiness level framework (Naval Postgraduate School Monterey CA).	Human readiness levels	Presents and evaluates a human readiness level framework akin to the technology readiness level framework that focuses on the human dimensions of technology development
21	[144]	Energy Equity Project (2022). Energy Equity Framework: Combining data and qualitative approaches to ensure equity in the energy transition (University of Michigan – School for Environment and Sustainability (SEAS)).	Energy equity project framework	The Energy Equity Project Framework is presented in an open-source document and acts as a holistic guide to measuring and advancing energy equity. The goal is that the framework is used to directly benefit Black, Brown, Native, frontline, and low-income communities.
22	[145]	Arnstein, S.R. (1969). A ladder of citizen participation. J. Am. Inst. Plann. 35, 216–224.	Community engagement	Introduces a typology of citizen participation using examples from three federal social programs: urban renewal, anti-poverty, and Model Cities. The typology, which is designed to be provocative, is arranged in a ladder pattern with each rung corresponding to the extent of citizens' power in determining the plan and/or program.
23	[146]	Esmalian, A., Wang, W., and Mostafavi, A. (2022). Multi-agent modeling of hazard–household– infrastructure nexus for equitable resilience assessment. Comput. Civ. Infrastruct. Eng. 37, 1491–1520.	Equitable resilience modeling	Develops a hazards-humans-infrastructure nexus framework that enables integrated modeling of stochastic processes of hazard scenarios, decision-theoretic elements of adaptation planning processes of utility agencies, and dynamic processes of water supply infrastructure performance.
24	-	Boudewijns, E. A. et al. (2022). Facilitators and barriers to the implementation of improved solid fuel cookstoves and clean fuels in low-income and middle-income countries: an umbrella review. The Lancet Planetary Health 6, e601–e612	Cookstove adoption	Umbrella review on the factors that influence the implementation of improved solid fuel cookstoves and clean fuels in low-income and middle-income countries. For improved solid fuel cookstoves, these factors included: cost; knowledge and beliefs about the innovation; and compatibility. For clean fuels

these factors included: cost; knowledge and beliefs about the innovation; and external policy and incentives.

Table E.1 Publications on failures resulting from equity-myopic approaches to clean energy technology *Research*.

N.	Citation	Publication	Topic	Description
1	[105]	Woodson, T. S., Hoffmann, E. & Boutilier, S. (2021). Evaluating the NSF broader impacts with the Inclusion-Immediacy Criterion: A retrospective analysis of nanotechnology grants. *Technovation* **101**, 102210	Inequalities in research	Study finds 109 out of the 300 grants feature research and grant activities that are inclusive, while 235 out of the 300 grants have research and grant activities that either maintain the status quo or predominately target advantaged groups. Of the 109 grants with inclusive broader impacts, 9 of them involve inclusive research that is intrinsic to the underlying work. In comparison there are 102 grants that feature inclusive research that is directly related to the research. Of those 102 direct-inclusive grants, 99 of them relate to broadening participation of women and underrepresented minority populations is science fields.
2	[106]	Woodson, T. & Boutilier, S. (2021). Impacts for whom? Assessing inequalities in NSF-funded broader impacts using the Inclusion-Immediacy Criterion. *Science and Public Policy* scab072 doi:10.1093/scipol/scab072.	Inequalities in research	Study analyzes National Science Foundation (NSF) project outcome reports and finds that advantaged groups are the most likely to benefit from NSF-funded research. The study also shows that certain areas of NSF research, such as Social, Behavioral, and Economic Sciences, more efficiently generate impacts for marginalized groups compared to other directorates. This paper further argues that persistent inequalities in broader impact statements limit the potential of R&D to increase prosperity and well-being, two of NSF's mandated goals.
3	[107]	Flegal, J. A. & Gupta, A. (2018). Evoking equity as a rationale for solar geoengineering research? Scrutinizing emerging expert visions of equity. *Int Environ Agreements* **18**, 45–61	Discourse of equity in geoengineering	Examines how notions of equity are being evoked by research expert advocates in geoengineering. Authors find that understandings of equity in "vanguard visions" are narrowly conceived as epistemic challenges, answerable by (more) scientific analysis. Essentially, major concerns about equity are treated as empirical matters that require scientific assessment. The authors argue that such epistemic framings sidestep the inequality in resources available to diverse non-experts—including the "vulnerable" evoked in expert visions—to project their own equity perspectives onto imagined technological pathways of the future.
4	[111]	Friedman, B. & Nissenbaum, H. (1996). Bias in computer systems. ACM Transactions on Information Systems (TOIS) **14**, 330–347	Bias in systems	Categorizes bias in computer systems: preexisting, technical, and emergent. Preexisting bias has its roots in social institutions, practices, and attitudes. Technical bias arises from technical constraints or considerations. Emergent bias arises in the context of use. Suggests options for identifying and remedying these biases.
5	[112]	Hofstra, B. *et al.* (2020). The Diversity–Innovation Paradox in Science. PNAS **117**, 9284–9291	Inequalities in research	Demographically underrepresented students innovate at higher rates than majority students, but their novel contributions are discounted and less likely to earn them academic positions. The discounting of minorities' innovations may partly explain their underrepresentation in influential positions of academia.
6	[113]	Kozlowski, D., Larivière, V., Sugimoto, C. R. & Monroe-White, T. (2022). Intersectional inequalities in science. *Proceedings of the National Academy of Sciences* **119**, e2113067119	Inequalities in research	Studies the relationship between scientists and the science they produce. Authors find a strong relationship between the characteristics of scientists and their research topics, suggesting that diversity changes the scientific portfolio with

				consequences for career advancement for minoritized individuals. Science policies should consider this relationship to increase equitable participation in the scientific workforce and thereby improve the robustness of science.
7	[114]	Muralidharan, N., Self, E. C., Nanda, J. & Belharouak, I. (2022). Next-Generation Cobalt-Free Cathodes–A Prospective Solution to the Battery Industry's Cobalt Problem. Transition Metal Oxides for Electrochemical Energy Storage 33–53	Negative consequences of material selection	Review summarizes the science and technology gaps and potential of numerous cobalt-free Li-ion cathodes including layered, spinel, olivine, and disordered rock-salt systems. Despite the promising performance of these Co-free cathodes, scale-up and manufacturing bottlenecks associated with these materials must also be addressed to enable widespread adoption in commercial batteries.
8	[115]	Banza Lubaba Nkulu, C. et al. (2018). Sustainability of artisanal mining of cobalt in DR Congo. Nature Sustainability **1**, 495–504	Negative consequences of material selection	Finds that people living in a neighborhood that had been transformed into an artisanal cobalt mine in Congo had much higher levels of cobalt in their urine and blood than people living in a nearby control area. The differences were most pronounced for children, in whom authors also found evidence of exposure-related oxidative DNA damage. This field study provides novel and robust empirical evidence that the artisanal extraction of cobalt that prevails in the DR Congo may cause toxic harm to vulnerable communities. This strengthens the conclusion that the currently existing cobalt supply chain is not sustainable.
9	[116]	Zeng, A. et al. (2022). Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. Nat Commun **13**, 1341	Negative consequences of material selection	Simulates historical (1998-2019) and future (2020-2050) global cobalt cycles covering both traditional and emerging end uses with regional resolution (China, the U.S., Japan, the EU, and the rest of the world). Shows that cobalt-free batteries and recycling progress can significantly alleviate long-term cobalt supply risks; however, the cobalt supply shortage appears inevitable in the short- to medium-term (during 2028-2033), even under the most technologically optimistic scenario.
10	[117]	Hsiang, S. et al. (2017). Estimating economic damage from climate change in the United States. Science **356**, 1362–1369	Unequal impacts of climate change	Constructs spatially explicit, probabilistic, and empirically derived estimates of economic damage in the United States from climate change. The combined value of market and nonmarket damage across analyzed sectors—agriculture, crime, coastal storms, energy, human mortality, and labor—increases quadratically in global mean temperature, costing roughly 1.2% of gross domestic product per +1°C on average. Importantly, risk is distributed unequally across locations, generating a large transfer of value northward and westward that increases economic inequality. By the late 21st century, the poorest third of counties are projected to experience damages between 2 and 20% of county income under business-as-usual emissions.
11	[131]	Whyte, K. (2018). Settler Colonialism, Ecology, and Environmental Injustice. Environ. Soc. *9*, 125–144. 10.3167/ares.2018.090109.	Indigenous perspectives of ecology	This article examines ways in which settler colonialism has undermined Indigenous ecological knowledge, leading to environmental injustices. Drawing on Anishinaabe intellectual traditions, the author introduces the concept of collective continuance, "a society's capacity to self-determine how to adapt to change in ways that avoid reasonably preventable harms."

Table E.2 Publications on opportunities to incorporate equity and justice considerations in clean energy technology *Research*.

N.	Citation	Publication	Topic	Description
1	[102]	Sovacool, B. K. *et al.* (2015). Integrating social science in energy research. Energy Research & Social Science **6**, 95–99.	Call for sociotechnical research	Reflects on the current state of the energy studies field and proposes recommendations for better integrating social science into energy research because realizing a future safe, low-carbon energy system that is reliable will require fuller and more meaningful collaboration between the physical and social sciences.
2	[103]	Fell, M. J., Roelich, K. & Middlemiss, L. (2022). Realist approaches in energy research to support faster and fairer climate action. Nat Energy **7**, 916–922.	Framework for understanding energy research contexts	Purposes increased use of 'realist' approaches in sociotechnical energy studies to inform rapid climate action. Realist approaches place emphasis on understanding the mechanisms by which outcomes of interventions come about and how they depend on contextual factors. This can inform and support action dedicated to supporting justice, interdisciplinary work, and urgent energy research. The authors consider both advantages and the limitations of the realist approach and present a guide.
3	[104]	Ravikumar, A. P. *et al.* (2023). Enabling an equitable energy transition through inclusive research. Nat Energy **8**, 1–4.	Equitable funding and diversity in research	Provides five key action items (reframing equity, direct engagement, resolving competing equity interests, expanding review and award criteria, and instituting structural reform) for government agencies and philanthropic institutions to pursue to operationalize their commitment to an equitable energy transition
4	[108]	van de Poel, I. & Taebi, B. (2022). Value Change in Energy Systems. Science, Technology, & Human Values **47**, 371–379.	Understanding values in the energy system	Discusses value changes in energy systems, different understandings of values and value change, and explains why the topic of values in energy systems and their design is important and how it can be methodologically studied.
5	[110]	Jenkins, K. E. H., Spruit, S., Milchram, C., Höffken, J. & Taebi, B. (2020). Synthesizing value sensitive design, responsible research and innovation, and energy justice: A conceptual review. Energy Research & Social Science **69**, 101727.	Incorporating energy justice into design and research	This paper considers Value Sensitive Design, Responsible Research and Innovation and Energy Justice literatures – all dedicated to improving the social outcomes and mitigating sensitivities at the interface of technological energy systems and human livelihoods. The authors synthesize the literature and demonstrate that these concepts can work in tandem to expand their practical applications, appreciate the full lifecycle of technologies, include a wider range of voices, and develop normative theory.
6	[121]	Dutta, N.S., Gill, E., Arkhurst, B.K., Hallisey, M., Fu, K., and Anderson, K. (2023). JUST-R metrics for considering energy justice in early-stage energy research. Joule 7, 431–437.	Metrics for evaluating EJ in early-stage research	Establishes a 'Justice Underpinning Science and Technology Research' (JUST-R) metrics framework for early-stage researchers to assess the energy justice impacts of their work on an immediate timescale. Themes include: hidden process costs, breadth of pre-existing knowledge review, distribution of research results, distribution of hazard exposure during the research life cycle, identification of set vs. flexible parameters.
7	[123]	Lane, M. K. M. *et al.* (2023). Green chemistry as just chemistry. Nat Sustain 1–11 doi:10.1038/s41893-022-01050-z.	Linking green chemistry and justice	Explores the potential for green chemistry and adjacent approaches to be leveraged to address existing environmental injustices. Highlights historical injustices and the need to rely on systems that can serve to enable progress rather than reinforce the status quo.

8	[125]	Mabey, C. S. et al. (2021). A computational simulation-based framework for estimating potential product impact during product design. Design Science **7**, e15.	Framework for estimating a technology's potential impact	Provides a framework for the estimation of product impact during product design. This framework integrates models of the product, scenario, society, and impact into an agent-based model to estimate product impact. Although this paper uses only social impact, the framework can also be applied to economic or environmental impacts individually or all three concurrently.
9	[126]	Salazar, G., See, J. E., Handley, H. A. H. & Craft, R. (2020). Understanding Human Readiness Levels. Proceedings of the Human Factors and Ergonomics Society Annual Meeting **64**, 1765–1769.	Human-focused analogy to TRLs	Proposes the Human Readiness Levels (HRL) scale to complement and supplement the Technological Readiness Levels (TRL) scale. Matures the HRL scale and evaluate its utility, reliability, and validity for implementation in the systems acquisition lifecycle.
10	[127]	Bernstein, M. J. *et al.* (2022). The Societal Readiness Thinking Tool: A Practical Resource for Maturing the Societal Readiness of Research Projects. Sci Eng Ethics **28**, 6.	Tool to facilitate social/ethical thinking in research	Introduces the Societal Readiness (SR) Thinking Tool to aid researchers and innovators in developing research projects with greater responsiveness to societal values, needs, and expectations.
11	[128]	Bozeman III, J. F., Nobler, E. & Nock, D. (2022). A Path Toward Systemic Equity in Life Cycle Assessment and Decision-Making: Standardizing Sociodemographic Data Practices. Environmental Engineering Science **39**, 759–769.	Systemic equity framework for decision-making	Presents a framework for integrating equity in energy and environmental research and practitioner settings, called systemic equity. Systemic equity requires the simultaneous and effective administration of resources (i.e., distributive equity), policies (i.e., procedural equity), and addressing the cultural needs of the systematically marginalized (i.e., recognitional equity). To help provide common language and shared understanding for when equity is ineffectively administered. Presents ostensible equity (i.e., when resource and policy needs are met, but cultural needs are inadequately met), aspirational equity (i.e., when policy and cultural needs are met, but resources are inadequate), and exploitational equity (i.e., when resource and cultural needs are met, but policies are inadequate).
12	[129]	Jones, A., Nock, D., Samaras, C., Qiu, Y. (Lucy), and Xing, B. (2023). Climate change impacts on future residential electricity consumption and energy burden: A case study in Phoenix, Arizona. Energy Policy *183*, 113811. 10.1016/j.enpol.2023.113811.	Climate modeling of cooling inequities	In this analysis, researchers evaluate how a warming climate will affect regional energy equity by tying temperature projections with household temperature response functions derived from smart-meter electricity data in Phoenix, Arizona. They find that the median elderly and low-income household percentage changes are nearly 5 percentage points higher than their counterparts after controlling for decadal, housing, and cooling infrastructural differences.
13	[132]	Mazzone, A., Fulkaxò Cruz, D.K., Tumwebaze, S., Ushigua, M., Trotter, P.A., Carvajal, A.E., Schaeffer, R., and Khosla, R. (2023). Indigenous cosmologies of energy for a sustainable energy future. Nat. Energy 8, 19–29.	Indigenous perspectives of the energy future	This review article explores Indigenous perspectives in energy research and practice. The authors identify three core issues embedded in existing energy-development initiatives: an inconsistent use of the term 'Indigenous'; a lack of inclusion of Indigenous knowledge and alternative epistemologies in energy-development projects; and a prevalence of inadequate methodological attempts to include such Indigenous knowledge.
14	[136]	Cronin, J. et al. (2021). Embedding justice in the 1.5°C transition: A transdisciplinary research agenda. Renew. Sustain. Energy Transit. 1, 100001. 10.1016/j.rset.2021.100001.	Transdisciplinary just energy transition research	Authors explore the justice implications of 1.5°C-consistent modeled pathways, focusing on fossil fuel extraction, critical resources, economic impacts and human needs. They identify three cross-cutting characteristics of just transitions: the inherently politicized nature of transitions; the need to integrate multiple perspectives; and the challenges they present to values and assumptions. Authors propose a research agenda which recommends ways in

				which research must be interdisciplinary, integrative of diverse actors and perspectives, and able to robustly test and explore radical ideas if researchers are to deliver just transitions to 1.5°C.
15	[137]	Stilgoe, J., Owen, R., and Macnaghten, P. (2013). Developing a framework for responsible innovation. Res. Policy 42, 1568–1580. 10.1016/j.respol.2013.05.008.	Responsible research and innovation	Presents a framework for understanding and supporting efforts aimed at responsible innovation based on four integrated dimensions of responsible innovation: anticipation, reflexivity, inclusion and responsiveness.
16	[138]	Anastas, P., and Eghbali, N. (2010). Green chemistry: principles and practice. Chem. Soc. Rev. 39, 301–312.	Green chemistry	Introduction to and critical review of green chemistry and its principles. Covers the concepts of design and the scientific philosophy of green chemistry with a set of illustrative examples.
17	-	Sovacool, B. K. et al. (2020). Sustainable minerals and metals for a low-carbon future. Science **367**, 30–33.	Sustainable minerals and metals sourcing	Identifies sustainability challenges with practices used in industries that will supply the metals and minerals (cobalt, copper, lithium, cadmium, and rare earth elements) needed for technologies like solar PV, batteries, electric vehicle motors, wind turbines, fuel cells, and nuclear reactors. Proposes four recommendations to make mining and metal processing more sustainable, just, efficient, and resilient.