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Justice-Embedded Requirements Engineering for System Design

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The clean-energy transition provides a unique opportunity to design a more just energy system. This paper introduces the Justice-Embedded Requirements Engineering (JERE) Process—an iterative process made to enable engineers to consider concepts of justice in their design of next-generation technologies, with a focus on energy technologies. To assess the JERE Process, five teams (n = 12) applied it to a project of their choosing and provided feedback through surveys and focus groups. JERE was found to elicit helpful conversations among teams and provide a structure for systematic engagement with justice considerations. Student researchers (n = 7) generally found JERE to be more usable, appealing, and impactful compared to professional participants (n = 5). Yet, overall, participants found the JERE tool prototype to be relatively difficult to use and found the length of the JERE Process and workshops challenging. Feedback from participants led to an updated version of the JERE Process that is simpler and modular. This study highlights difficulty engineers and researchers may face when attempting to practically embed justice principles in their technical design work and can assist those attempting to ensure technical solutions can support the goals of a more just, clean-energy system.
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1 Introduction

1.1 Frontline Communities and the Energy System. As various nations and intergovernmental bodies aspire to reach critical decarbonization targets, it has become imperative to develop and deploy clean and efficient energy technologies that work for all. Members of vulnerable and overburdened communities ("frontline communities") have historically been invisibilized and marginalized in decarbonization efforts despite facing the first and worst consequences of both climate change and the existing fossil-fuel-based energy system [1]. Due to both climate change and the current energy system, frontline communities face poor air and water quality, physical and mental health challenges, deeper social inequality, loss of livelihoods, higher energy burdens (ratio of energy expenditure to income), and energy insecurity [1–3]. Further, frontline communities also struggle to access renewable energy technologies and the many benefits associated with these technologies [4,5].

Considering the injustices frontline communities face, local, national, and international governing bodies now seek to pursue a "just energy transition" that will remedy the injustices of the fossil-fuel-based energy system and extractive economy while building a system of "dignified, productive, and ecologically sustainable livelihoods; democratic governance; and ecological resilience" [1]. A just energy transition also aims to avoid future harms to individuals and communities who rely on the existing fossil-fuel-based energy system for their livelihoods [3]. Fifty percent of technologies needed to hit decarbonization goals are now in the prototype or demonstration stage [6], making it an opportune time to consider justice and equity in how we design the next generation of renewable energy technologies and the system they will beget before inequities are further locked into the forthcoming clean-energy system [7].

This article seeks to answer the research question: "How can justice be embedded in the design of next-generation clean and sustainable energy technologies?" Here, we introduce the *Justice-Embedded Requirements Engineering (JERE)* Process. JERE (pronounced "jerry") was created to enable engineers to consider justice in their design of next-generation technologies. Informed by energy justice and design literature, JERE provides a detailed process—consisting of questions, lists, and guided exercises—for engineers to deeply consider project goals, requirements, and potential project impacts on frontline communities from the earliest stages of system design. The entire JERE Process is available in the supplementary material (section S1, available in the Supplemental Materials on the ASME Digital Collection), which can be downloaded at https://github.com/bettinark/JERE/blob/main/JERE Article Supplementary.pdf.

This article was written in the context of the United States with the hope that the work presented here could also be amended or broadened, if necessary, to apply to other nations.

1.2 Energy Justice. A critical component of both JERE and the pursuit of a just energy system is the concept of energy justice. Energy justice is a principle to achieve equity in the participation in, and outcome of, the energy system, while also remediating social, economic, and health burdens on those historically

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harmed by the energy system (adapted from Ref. [1]). Here, "equity" consists of recognizing and addressing each person's circumstances and allocating resources and opportunities needed to "level the playing field," or reach an equal or fair outcome (adapted from Ref. [8]). Although many energy justice concepts are found in literature, five—distributional, procedural, recognition, restorative, and intergenerational justice—will be referenced in this article. These concepts are both prevalent in the literature and span the *where* (distributional), *how* (procedural), *who* (recognition), and *when* (restorative and intergenerational) dimensions of energy justice [9].

Distributional justice deals with the equitable distribution of benefits and burdens of the energy system across a population. It can span geographical, social, economic, and temporal contexts. Distributional justice considers to whom benefits accrue, where burdens occur, and whether the burdens disproportionately affect frontline communities [10]. Procedural and recognition justice consider how to tackle injustice and for whom, respectively. Procedural justice focuses on equitable engagement, fairness, and transparency when allocating resources and adjudicating disputes. It involves understanding who has a seat at the proverbial table, who is involved in decision-making, and what concerns of inclusiveness and influence are at play in a process [1,10].

Intergenerational justice considers multiple generations when evaluating the changing effects of energy technologies over time. Intergenerational justice considers a population's obligations to future generations and takes action that increases, rather than limits, the options of future generations [11,12]. Restorative justice seeks to acknowledge, ameliorate, and address previous negative impacts and inequities from the energy system, especially as they pertain to frontline communities [1,13]. Understanding the geographical, cultural, and historical contexts of energy justice is particularly important given diverse views of justice across different regions, nations, cultures, and populations.

1.3 Designing More Just Systems. Designing more just technologies in order to construct more just systems is a goal of "systems justice," which "connects [a] bird's eye view of justice … to the distinctive position of each agent in a social system … it is a lens through which moral agents can see the world from different vantage points and motivate their distinctive contribution to global justice" [14]. Essentially, systems justice contends with the "problem of many hands," in which traditional understandings of responsibility for injustice break down in large, complex, and multi-actor systems [14,15]. In these systems, it may be difficult, if not impossible, to pinpoint the group of responsible actors or perpetrators because injustices do not arise from individual agents, but rather from the collective. van de Poel et al. point to examples such as climate change to illustrate the problem of many hands because, in such cases, "the collective may be responsible for an undesirable outcome but none of the individuals in the collective is responsible" [15].

Applying a perspective of systems justice, each energy engineer and practitioner is a moral agent with a role to play in pursuing a more just energy system; yet, current engineering practice and literature lack the necessary tools to enable engineers to meaningfully incorporate concepts of energy justice in their work. Energy justice, which is informed by community, environmental, and climate justice advocacy, has historically resided in social science, policy, and legal literature [1,9]. This article aims to embed energy justice in the technology design process through the creation, introduction, and preliminary assessment of the JERE Process.

1.4 Article Overview. Subsequent sections of this article will describe the creation and steps of the JERE Process, the JERE tool prototype, case study evaluations of JERE, and an updated JERE Process based on evaluation results. The JERE Process is grounded in existing energy justice, Value-Sensitive Design, Responsible Research and Innovation, and Design Justice literature; therefore, a short review of relevant techniques to incorporate justice in system design is provided.

1.5 Literature Review: Justice-Centered Design

1.5.1 Review of Design Frameworks and Methods for Incorporating Justice. Although systems justice applies to energy systems, we still lack well-developed, practical tools for energy engineers, developers, and practitioners to thoroughly embed concepts of justice into their work. Therefore, we carried out a literature review of the most common design frameworks and methodologies for embedding justice considerations, or similar values, into the technology design process. We particularly focused on frameworks and methodologies that provide practitioners with clearly defined steps. The major frameworks and techniques reviewed were (1) Value-Sensitive Design (VSD), (2) Responsible Research and Innovation (RRI), (3) Design Justice, and (4) System Design for Sustainable Energy for All (SD4SEA). Other relevant design frameworks were also studied in this literature review and are mentioned alongside these major ones. More in-depth literature reviews that focus on the intersections of justice and design can be found in Refs. [16–18]. However, although there are several proposed methods for incorporating justice in research, engineering, and design processes, there is generally a lack of rigorous evaluation of methods, making it difficult to fully understand the impact or effectiveness of these techniques.

The literature around justice and design tends to be made up of two main branches. One branch involves the philosophical underpinnings and theories of justice in the context of design—what is meant by "justice," what are its sociopolitical implications in design, what are the designer's moral prerogatives, and so on [15,19–23]. The other branch focuses on integrating justice into design work, mostly by focusing on injustices that emerge from technologies or by encouraging designers to center marginalized communities in the design process using methodologies such as participatory design and human-centered design [14,16,24]. When it comes to design processes that fall into the latter category, one often finds repeated themes of community empowerment, deep collaboration, continuous self-reflection, bias identification, and consciousness around power dynamics in the design process [16,25,26].

1.5.2 Value -Sensitive Design. Value-Sensitive Design is a design framework through which "researchers and designers can explicitly incorporate the considerations of human values into their work" [27]. Values may be broadly defined as "varieties of goodness" as deemed by the stakeholders [24]. VSD has historically been applied in the field of human–computer interaction but has implications for fields ranging from technology design and engineering to policy and governance [24,28,29]. VSD consists of three iterative steps: conceptual investigations, empirical investigations, and technical investigations (Fig. 1) [27]. Conceptual investigations involve identifying direct stakeholders (those who will use the product) and indirect stakeholders (those who are impacted by others' use), as well as identifying and defining the values implicated by use of the technology. Empirical investigations aim to understand the stakeholders, their experiences, actions, knowledge, and contexts. In terms of energy justice principles, the empirical investigation could be used to enhance recognition justice. Finally, the technical investigation seeks to understand how values can influence various features of new or existing technologies [27].

In an attempt to link VSD and energy justice, Jenkins et al. (2020) indicate that energy justice can further inform VSD by emphasizing the frontline communities who may be indirect stakeholders in the design process, providing ethical theory for VSD, and incorporating more of a systems-wide vantage for the application of VSD in the design of energy systems. VSD has also been

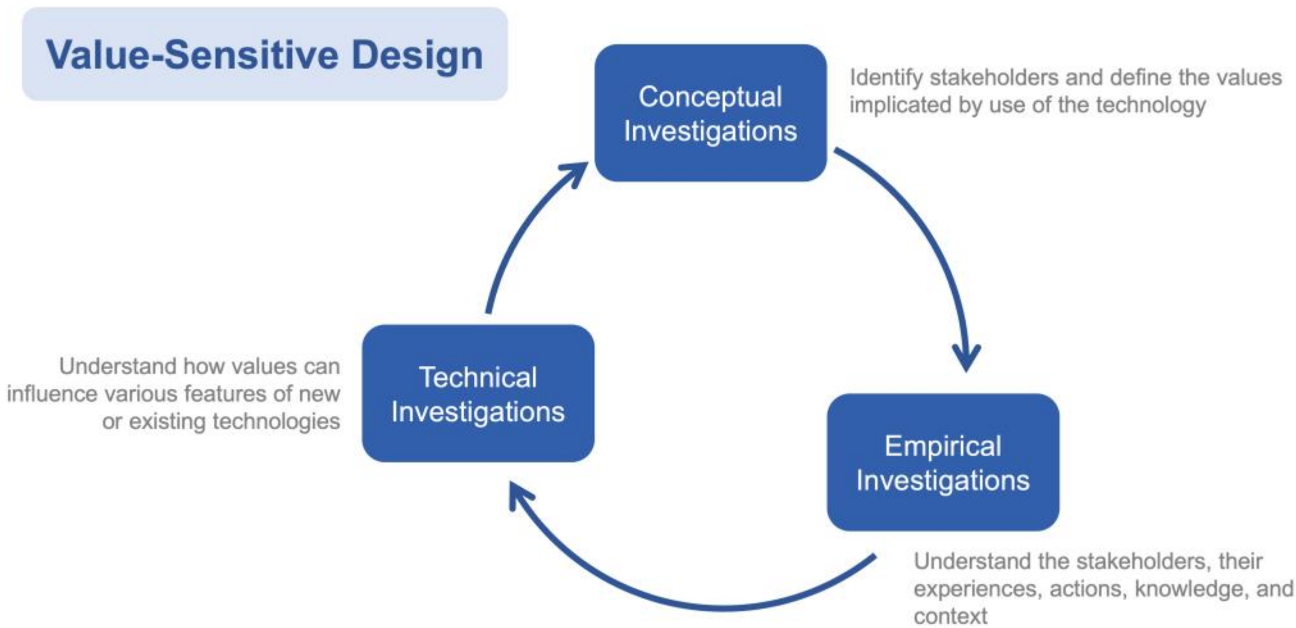


Fig. 1 Investigative cycle in value-sensitive design (VSD)

used in the energy space via a case study for solar panel deployment in Finland, in which researchers worked with stakeholders to install rooftop solar in a manner that aligned with stakeholder esthetic values and cultural preferences [29]. Compared to traditional product design, VSD will likely look different in energy system design, given the expansive scope and broad range of values and stakeholders associated with capital energy projects. This breadth is especially vast when considering intergenerational justice, in which future generations will not necessarily be able to meaningfully inform contemporary design choices [27]. Because a technology's influence is shaped not only by features of its design but also by the context in which it is used and the people using it, a major limitation of VSD, and all other anticipatory frameworks, is the inherent lack of knowledge of how a technology's use will evolve with time [19].

1.5.3 Responsible Research and Innovation. Responsible Research and Innovation is a framework that aims to transparently and interactively create conditions in which "societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability, and societal desirability of the innovation process and its marketable products" [22]. RRI is often referenced in academia and policy at the intersection of technology and public good [21]. In practice, RRI is typically marked by four dimensions synthesized by Stilgoe et al. (2013): anticipation, reflexivity, inclusion, and responsiveness. Anticipation is meant to encourage researchers, innovators, and their organizations to ask "what if" questions to better understand issues that may arise from their research or new technologies [26]. Stilgoe et al. define institutional reflexivity as "holding a mirror up to one's own activities, commitments and assumptions, being aware of the limits of knowledge and being mindful that a particular framing of an issue may not be universally held." Reflexivity can be either institutional or individual. Institutional reflexivity seeks to scrutinize the value systems and theories that shape science, innovation, and their governance. In contrast, individual reflexivity is more of a reflection and self-critique by individual actors regarding their own work.

Similar to how the principle of anticipation is found in both VSD and RRI, along with several other justice-oriented design frameworks presented in the literature, reflexivity is another common principle found among many of the methodologies reviewed. This theme is apparent in design processes such as Liberatory Design, which strives to generate self-awareness for designers to curb habits that perpetuate inequity, shift the relationship between "the people who hold power to design and those impacted," empower those influenced by the design work, and "create conditions for collective liberation" [25]. Reflexivity in practice could also resemble designers systematically answering a series of questions to understand the potential social justice implications of their work [17,30,31] Fig. 2.

The RRI principle of inclusion centers engaging new voices in the governance of science and innovation, while responsiveness focuses on responding to new knowledge and making changes as it emerges [26]. As with applying energy justice principles, RRI seeks to positively impact society and can enable the inclusion of frontline communities in research and innovation, even though their needs are not necessarily the main focus of RRI. Attempts have been made to link RRI with concepts of energy justice, energy policy, and VSD [20,28]. For example, Dutta et al. (2023) introduced the Justice Underpinning Science and Technology (JUST-R) metrics framework, which was created across dimensions of energy justice and RRI for early-stage and basic science researchers to consider the justice implications of their energy research [32]. Yet, overall, the RRI literature remains lacking in concrete, familiar, and directly applicable methods for engineers who seek to design more just energy technologies and systems, which highlights the need for Design Justice.

1.5.4 Design Justice. Design Justice, pioneered by Sasha Costanza-Chock and the Design Justice Network, is a framework that "rethinks design processes, centers people who are normally marginalized by design, and uses collaborative, creative practices to address the deepest challenges our communities face" [16]. Design Justice is characterized by community stewardship, expertise, and empowerment, as well as reflective, collaborative, and non-exploitative design processes. It encourages the designer to reflect on the values, practices, narratives, locations, and pedagogies of design and more systematically address inequities. In an expansion of Design Justice, Das et al. present a framework for equitable engineering design and research, which provides a series of questions related to equity, ethics, and justice for engineers and designers to answer [17]. Questions fall in a range of categories from equity, history, and values to problem scope, design

Fig. 2 Dimensions of responsible research and innovation (RRI)

beneficiaries, and sustainability. Similarly, Santos Ayllón et al. introduced the Justice by Design framework and methodology for energy practitioners, technologists, developers, investors, policymakers, and community groups to scrutinize the justice implications of energy projects [33].

The expanded Design Justice framework structure, the Justice by Design framework, and several of the questions they pose, resonate with a framework introduced by Romero-Lankao et al. to center justice in energy innovation, dubbed the "CJI framework" (a framework to centre justice in energy transition innovations) [31]. The CJI framework presents a series of questions to enable energy practitioners to view procedural, distributional, and recognition justice dimensions of the energy system across three increasing analytical levels—niche (research and development), regime (mature energy transition innovations), and landscape (broader cultural paradigms). The CJI framework is then applied to two case studies, one focused on wind energy in Mexico and another centered on the Los Angeles 100% Renewable Energy Study. The CJI framework enabled multilevel inspection of the justice in these two case studies.

Although these frameworks enable engineers to think more holistically and reflect on the justice implications and contexts in which they work, engineers may still find it difficult to meaningfully apply their reflections to their typical design activities, especially without an accessible tool or detailed protocol. Additionally, many methods that incorporate aspects of justice, or related concepts, may be inaccessible to energy engineers given their specialization in particular technical areas within the energy sector. They may not have any philosophical grounding or knowledge of their work's potential sociotechnical impacts, especially if they have little interaction or familiarity with marginalized groups.

1.5.5 Energy System Design for Global Development. Renewable energy design and implementation for global development oftentimes reflect the energy justice principles of procedural and recognition justice. This alignment is particularly apparent in the case of Vezzoli et al.'s (2018) attempt to design sustainable distributed energy systems and processes for use in the Global South. The process they introduce, "System Design for Sustainable Energy for All" or SD4SEA, incorporates concepts such as design for sustainability, human-centered design, and participatory design. The goal of SD4SEA is to design a sustainable product-service system to fulfill the demand for distributed renewable energy in low- and middle-income populations [34]. This framework considers the potential users (i.e., low- and middle-income populations), their circumstances, and how they are engaged (i.e., through deep user-centered collaboration) throughout the design process.

SD4SEA is broken into five stages: strategic analysis, exploring opportunities, designing system concepts, designing system details, and communication [34]. At the strategic analysis stage, the design team aims to understand local contexts, which enables them to design sustainable energy products in a specific location. The design team then explores opportunities through participatory design for various stakeholders to generate ideas at the system level. These ideas are aggregated and distilled in order to design one or more system concepts. Next, the detailed system design process begins, during which the design team develops the most promising system concept into a detailed version for implementation (Fig. 3). Finally, the design team creates documentation for internal and external communications. Although SD4SEA was created to be used in the Global South, its thoughtful incorporation of procedural and recognition justice and guidance for thinking more holistically about integrating users, their satisfaction, and details of local contexts into energy technology design processes made this framework particularly relevant for understanding mechanisms for operationalizing justice in renewable energy design.

1.5.6 Gaps in the Literature. Even with all of the aforementioned methods and frameworks that may be applicable for incorporating energy justice in the technology design process, none have been well-embedded in the work of energy engineers and researchers—exemplifying existing gaps. These gaps fall into three categories: context, accessibility, and perceived responsibility.

Regarding the *context* gap, the energy sector can range from projects and products for single users and households to national and multinational systems and supply chains. If methodologies are not better tailored to the needs of engineers in this sector or the context in which they work, encouraging uptake of these methods and their accompanying principles will likely be difficult. Furthermore, the methods that provided the most familiar processes for energy engineers and researchers, such as VSD, lacked consideration of a broader justice-based framework, such as frameworks that come from considering various tenets of energy justice.

When it comes to *accessibility*, many of the methods that incorporate aspects of energy justice, or related concepts, may be inaccessible to energy engineers, given that they have likely specialized in particular technical areas within the energy sector. Thus, they may not have knowledge of the philosophical grounding or sociotechnical impacts of their work, particularly if they have little interaction or familiarity with marginalized groups. This gap provides evidence that energy justice-centered interventions better suited for this technology-focused audience are still necessary.

Finally, there is the issue of *perceived responsibility* or domain. Gaps in context, lack of accessibility, and even a simple lack of

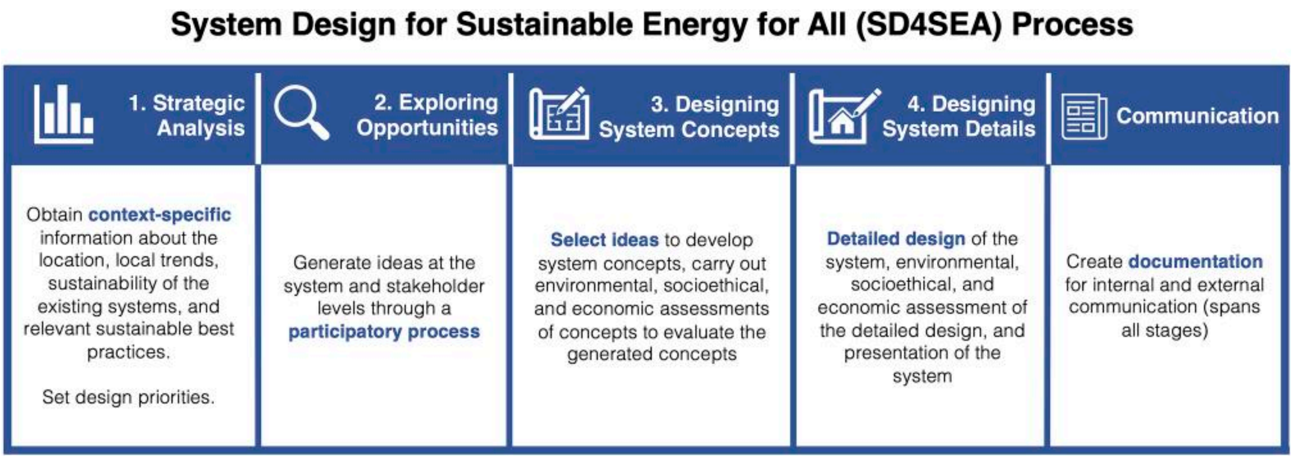


Fig. 3 System design for sustainable energy for all (SD4SEA) process breakdown

exposure to justice concepts lend themselves to a disconnect between the work of the individual engineer or researcher and the impacts of large, complex systems on frontline communities. This work strives to fill these gaps of context, accessibility, and perceived responsibility.

Times of major transition provide unique opportunities for us to reevaluate how we design and develop technology as engineers. If we do not incorporate equity and justice in this transition to a clean-energy system, we run the risk of repeating history by relying on the same techniques that caused the inequities we see today [35]. Although informed by several design frameworks and methodologies described in this literature review, the Justice-Embedded Requirements Engineering (JERE) Process was particularly influenced by principles of Value-Sensitive Design (VSD).

2 The Justice-Embedded Requirements Engineering Process

2.1 Creating the JERE Process. van de Poel's VSD work that translates values into design requirements greatly influenced the design of the JERE Process [36]. In van de Poel's framework, values are translated into technical requirements through "norms." The term "norm" is used for "all kinds of prescriptions for, and restrictions on, action" [36]. van de Poel provides the example of "end-norms," which are particular objectives of a design process or attributes a designed artifact should possess. In the tripartite hierarchical framework of "values-norms-requirements" that van de Poel presents, values beget norms that influence actions in the design process, and norms then translate the impacts of those actions into requirements.

For this article, "requirements" will state the objectives of the system or technology that is created during a team's application of the JERE Process. These requirements will define the success of the project along with other important aspects like a system's functionality, cost, and quality. "Specifications" will be used for the more concrete, often quantifiable objectives of a system (e.g., system dimensions, electric output, rotations per minute, thermal conductivity, etc.). As one moves from values to requirements to specifications, the system's form and function become less ambiguous.

Criteria that informed the creation of the JERE Process are listed in Table 1. Each criterion is labeled either "Demand" or "Want" to indicate if the criterion *must* be included in the design intervention or if it would simply *be nice* for the criterion to be included in the design intervention, respectively. The list of criteria that led to the creation of the JERE Process was inspired by VSD, our team's literature review, surveys, and interviews with energy practitioners, and our team's prior research studying preliminary outcomes of incorporating energy justice metrics in energy research and development [7]. Our team found several gaps that needed to be addressed to enable energy researchers and engineers to apply justice to their work, including the need for more specialized tools, early-stage interventions, support for more concretely connecting justice principles to technical work, and assistance with solution follow-through [7]. These findings informed the creation of the criteria listed below. These criteria center on goals such as ensuring the intervention would be understandable and accessible to engineers, enhancing understanding of justice principles, and

Table 1 Criteria for creating the justice-embedded requirements engineering (JERE) process

Problem Statement: Help engineers embed energy justice into their energy engineering design process

	Priority	Criteria that informed JERE's creation	Primary Source
1	Demand	Make intervention understandable for engineers	Prior studies
2	Demand	Make intervention familiar to make it accessible to engineers	Prior studies
3	Demand	Enhance understanding of energy justice problem space	Prior studies
4	Demand	Enhance energy justice-based problematization for engineers	Prior studies
5	Demand	Increase method uptake	Lit review
6	Want	Provide flexibility to account for project or work diversity	Lit review
7	Want	Enhance perceived responsibility for engineers regarding energy justice considerations	Prior studies
8	Want	Enhance incentives for engineers to integrate energy justice	Prior studies
9	Want	Elucidate engineers' values	Lit review
10	Want	Enhance understanding of energy justice solution space	Prior studies
11	Want	Provide energy justice assessment for engineers	Lit review
12	Want	Provide justice-based decision support for engineers	Prior studies
13	Want	Enhance engineers' comfort with engaging with energy justice	Lit review
14	Want	Enhance systems-level understanding or approach	Lit review
15	Want	Enable meaningful consideration of diverse perspectives	Lit review

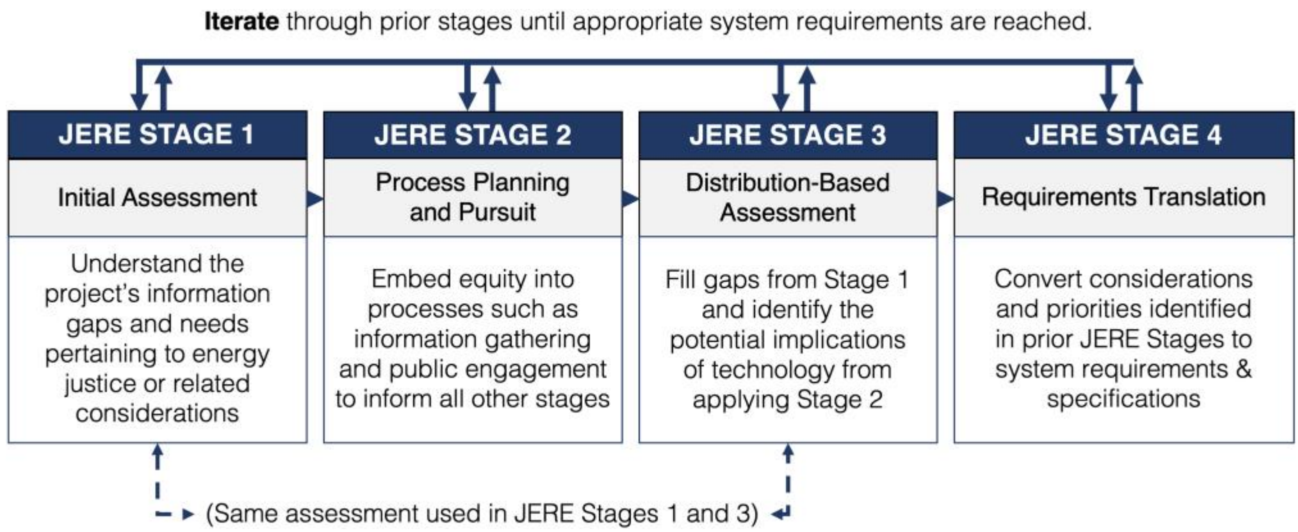


Fig. 4 Overview of the original justice-embedded requirements engineering (JERE) Process

supporting justice-related problematization and solution identification in engineering projects.

2.2 JERE Process Description. JERE's main goal is to enable early consideration and integration of energy justice principles in the energy technology design process. As shown in Fig. 4, the original JERE Process, before undergoing updates after user feedback, was broken down into four iterative stages: (i) Initial Assessment, (ii) Process Planning & Pursuit, (iii) Distribution-Based Assessment, and (iv) Requirements Translation. A hypothetical example of working through the original JERE Process can be found in section S2, available in the Supplemental Materials.

Stage 1. Initial Assessment: Understand the project's information gaps and needs pertaining to energy justice or related considerations. JERE Stage 1 is broken down into the following three steps: (i) a *Spatial Justice Assessment*, which focuses on a project's geographical distribution of benefits and burdens across technological, environmental, economic, cultural, and political dimensions; (ii) a *Structural Justice Assessment*, which maps those benefits and burdens to 15 demographic characteristics (e.g., ethnicity, wealth, gender, and climate vulnerability); and (iii) consolidation of gaps identified in this first stage of JERE. The Spatial and Structural Justice Assessments form the Distribution-Based Assessment found in JERE Stage 3. During the Spatial Justice Assessment, the team is prompted to consider where the technology will be designed, demonstrated, and eventually deployed. These considerations are brought to the forefront to highlight potential discrepancies in where the work is being done and where the outcomes of the project will be realized. Engineers are also prompted to consider the primary (directly engaged or influenced), secondary (indirectly engaged or influenced), and tertiary stakeholders (affected downstream of secondary stakeholders) and principal (most salient and direct), ancillary (secondary or indirect), and possible (potential with high uncertainty) benefits and burdens associated with their project.

The Structural Justice Assessment maps project benefits and burdens to fifteen demographic characteristics users can choose from: race/ethnicity, language, wealth/income, occupation, disability, climate vulnerability, social vulnerability/marginalization, age, body dimensions, housing status, gender, sexual orientation, religion, educational background, and regional issues of injustice. It encourages users to think more specifically and systematically about who is expected to be a beneficiary or adversely affected by their project. Along with these fifteen demographic considerations is the opportunity for JERE users to both think about the intersections of these demographic considerations and define their own demographics. Users are encouraged to think through each demographic consideration across time, assessing the historical, contemporary, and anticipated benefits and burdens of project outcomes on each group. The final step of JERE Stage 1 is the "Gap Consolidation" step. In preparation for JERE Stage 2, the "Gap Consolidation" step guides users as they aggregate, arrange, and consolidate the information gaps and needs they identified in the Initial Assessment. Throughout JERE Stage 1, users are encouraged to keep track of information gaps that need to be filled as they go through the JERE Process.

Stage 2. Process Planning and Pursuit: Embed equity into processes such as information-gathering, communication, and public engagement to inform all other stages of JERE. This stage focuses on incorporating procedural justice into design processes and filling knowledge gaps identified in Stage 1. This portion of the JERE Process consists of six steps: (i) identifying the project's information gaps and needs, particularly as they relate to justice considerations (completed through JERE Stage 1); (ii) planning the project's information-gathering protocol, which includes identifying equity-centered frameworks and data collection methods; (iii) developing the project's decision-making and communication protocols; (iv) gathering the necessary information to fill gaps identified in JERE Stage 1; (v) communicating results to team members, partners, stakeholders, etc.; and (vi) incorporating the findings into the Distribution-Based Assessment (JERE Stage 3). JERE Stage 2 provides several examples of frameworks, techniques, and factors for users to consider applying to their projects, including project co-development, participatory design, VSD, and considerations such as transparency, compensation for partners, safety, and mediation to address power imbalances.

Stage 3. Distribution-Based Assessment: Identify and assess potential distributional justice implications of technology based on findings from Stage 2. This stage uses the same assessment as JERE Stage 1. Users are prompted to reconsider and reevaluate the potential benefits and burdens associated with the project and how they may be distributed in time, space, and across demographics. The three steps of JERE Stage 3 are as follows: (i) Spatial Justice Assessment; (ii) Structural Justice Assessment, and (iii) consideration and priority identification. After users revisit the Distribution-Based Assessment (Spatial and Structural Justice Assessments), the final step of JERE Stage 3 focuses on identifying the major considerations and priorities that arose from JERE Stages 1–3. Users take these priorities into the final

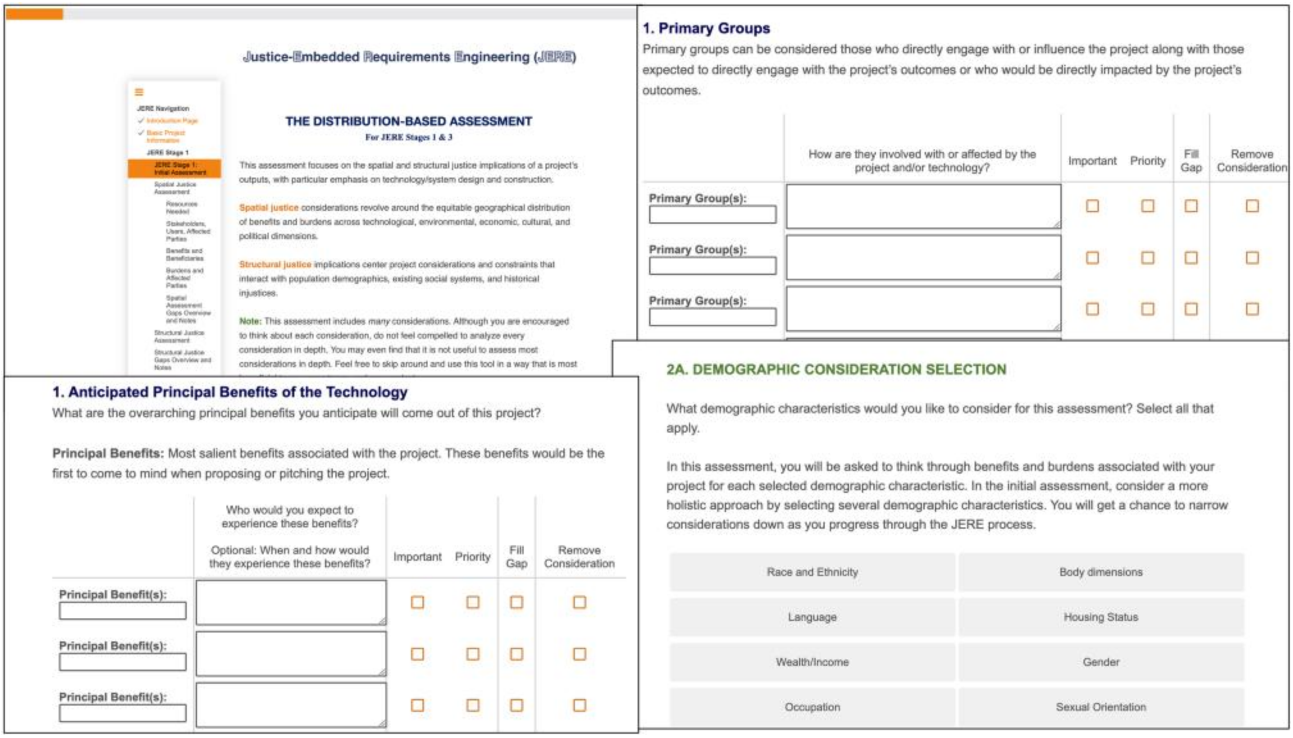


Fig. 5 Screenshots of the JERE prototype built in Qualtrics

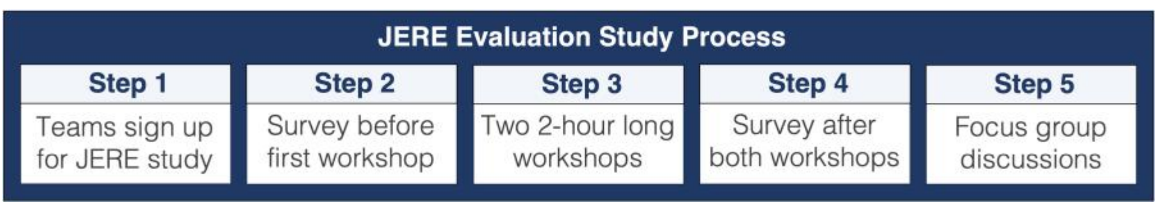


Fig. 6 Overview of the JERE evaluation process

stage of JERE, during which they identify requirements based on their findings.

Stage 4. Requirements Translation: Convert the information and priorities identified in Stages 2 and 3 to system requirements and specifications. During the final stage of JERE, users identify project objectives, constraints, and relevant justice considerations; reconcile tensions across these factors; and consolidate and clarify the project requirements and specifications. Stage 4 consists of seven steps: (i) identifying areas of optimization for benefits; (ii) identifying areas of mitigation for burdens; (iii) understanding and addressing points of tension and tradeoffs; (iv) prioritizing considerations; (v) translating considerations into requirements; (vi) prioritizing requirements; and (vii) translating requirements into specifications.

To allow users to go through the JERE Process more easily, a JERE tool prototype was built using the Qualtrics© (Provo, UT) online survey maker. This tool was chosen for creating the prototype because it provided a simple user interface for building the prototype quickly, enabled data storage that allowed users to save their work and return to it, and allowed the prototype to be distributed online Fig. 5.

3 Evaluating the JERE Process

3.1 Goals of JERE Evaluation. After creating the JERE Process, we sought to understand the effectiveness and appeal of the process and tool prototype. "Effectiveness" was defined in terms of "usability" (whether JERE is accessible, understandable, and capable of being applied) and "perceived impact" (seen as meaningfully influencing design decision-making and processes), as defined in Ref. [7]. Along with JERE's effectiveness, we sought to assess: the appeal (evoking demonstrated interest, value, or enthusiasm) of the process and tool prototype, along with the circumstances under which engineers would engage with JERE, and their recommended improvements for the JERE Process and tool.

Overall, the JERE Evaluation study sought to answer the following five research questions:

(1) How usable is the JERE prototype?
(2) How impactful do participants perceive the JERE Process and prototype to be?
(3) How appealing do engineers find the JERE Process and prototype?
(4) When and how do engineers engage with JERE?
(5) What can be done to improve JERE's effectiveness and appeal?

3.2 JERE Evaluation Study Methods. To answer the research questions, teams participated in JERE workshops and provided feedback on both the JERE Process and the tool prototype. This study was approved by the Institutional Review Board (IRB) of the Georgia Institute of Technology, and informed consent was obtained from all participants. First, five teams of two to eight people were recruited for the study via recruitment posts on social media and recruitment emails. Interested teams had to fill out an online interest form to alert the research team of their interest. Every member of the team needed to meet the following requirements:

- Currently researching, engineering, designing, and/or demonstrating technology in the energy sector.[2]
- Be a fluent English speaker.
- Live in the United States or a territory of the United States.
- Be able to give written consent.
- Be 18 years of age or older.

3.2.1 Data Collection Methods. Once we ensured all participant criteria were met, we scheduled the study with the team. The study consisted of two 2-hour long virtual workshops in which participants completed a short (~5 min) initial survey, were introduced to the JERE Process and tool prototype (~10 min), went through the JERE Process (~3 h), responded to a final survey (~15 min), and concluded by participating in a 30-minute focus group session. With participants' consent, these virtual workshops were recorded and transcribed. The overview of the evaluation study process is depicted in Fig. 6.

Teams were expected to have a project, proposal, or idea in mind that they would like to apply the JERE Process to. The virtual workshops were conducted via video calls on Microsoft® Teams. For each workshop, the team would select one team member to act as the "team guide." The team guide's screen would be shared with the rest of the team, and the team guide would be responsible for inputting information into the JERE tool prototype since only one participant could save information in the prototype at a time.

The first two-hour workshop was designed to include the initial survey, an introduction to JERE, and time to work through JERE Stages 1 (Initial Assessment) and 2 (Process Planning and Pursuit). The initial survey was used to gather data regarding the participants' work, their goals for the JERE workshop, exposure to, and familiarity and comfort with, energy justice and energy justice-focused resources. Likert scales were used to capture participants' initial sentiments around energy justice and applying it to their work. Teams were provided 60 min for the first stage of the JERE Process and 20 min for the second stage of the JERE Process, with an optional 5-minute break in between. The workshop facilitator mainly played the role of an observer and timekeeper, and would only provide ideas, thoughts, and clarifications when participants explicitly asked.

The second workshop consisted of a refresher on the JERE Process and tool prototype, working through JERE Stages 3 (Distribution-Based Assessment) and 4 (Requirements Translation), the final survey, and a team focus group. Teams were generally provided 40 min to work through JERE Stage 3 and 40 min to work through JERE Stage 4, with an optional five-minute break in between these stages. The final survey was similar in form to the initial, with many of the same Likert scale questions. The final survey also included questions on the ease and difficulty of the overall JERE Process and each of its stages, along with areas for participants to provide feedback on JERE's usability and appeal.

Focus group questions were as follows:

- At the end of this process, do you think JERE has impacted you or your work in any way? If so, how?
- In the future, could you imagine yourself going through the JERE Process again? And, if so, under what circumstances would you use it?
- Are there any improvements or suggestions you have around this workshop or the JERE Process?
- Is there anything else you would like to share or discuss?

Each participant was compensated with a $50 virtual gift card for each workshop attended. The total compensation for attending both 2-hour workshops was $100 in virtual gift cards. If participants were not able to stay for a two-hour block, their compensation was prorated up to the nearest half hour.

3.2.2 Data Analysis Methods. When analyzing the survey data, we compared the initial and final survey results for each participant. Both inductive coding and quantitative methods (frequency analysis and summary statistics) were used to extract trends from the survey data. Inductive coding and frequency analysis were also used for analyzing the focus group data in order to extract and understand trends in responses. Information from focus group sessions and participant observation also provided additional context around trends observed in survey data analysis.

All data collected and analyzed were associated with the five aforementioned research questions. Survey data primarily provided information on the usability, perceived impact, and appeal of the JERE Process and tool prototype. Observations made during the workshop pointed to the JERE prototype's usability, how technical teams engage with it, and ways it could be improved. The focus group data primarily provided information about how impactful participants felt JERE was, when, and how they could envision engaging with it in the future, if at all, and how they thought it could be improved.

4 JERE Evaluation Results

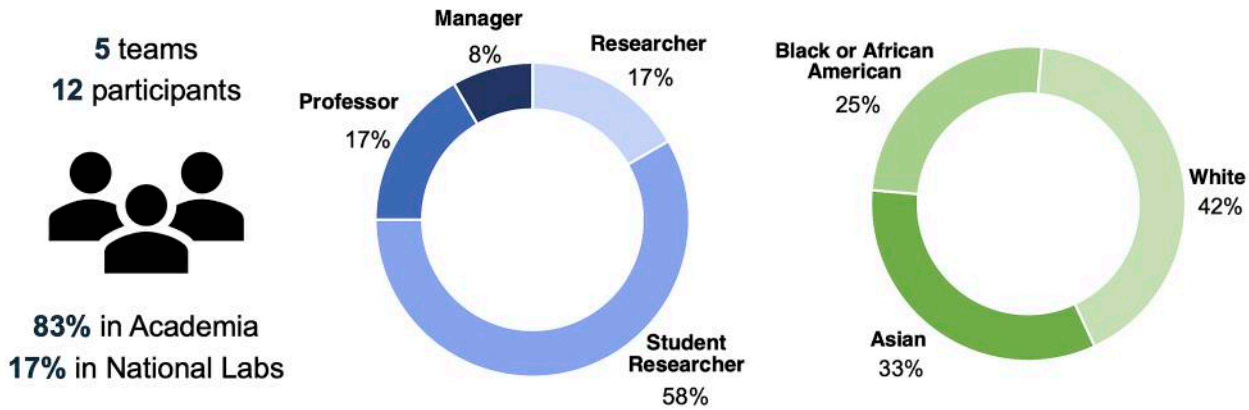
4.1 Overview of Participants. Five teams, comprised of 12 participants, took part in the JERE evaluation study. The majority (83%) of participants came from academia, and the remaining 17% came from national laboratories. 75% of participants were from the Southeastern USA, 17% from the Western USA, and one participant from the Northeast. Team projects spanned several topics, including energy, climate mitigation, mining, computation, and adaptation. A brief description of each team that participated in the study and the projects to which they applied JERE is provided. Additional information about participants, their prior experiences with energy justice, and why they decided to participate in this study is provided in the supplementary material (section S3.1, available in the Supplemental Materials).

- Team A: Two team members from a national laboratory working on an international electric charging project.
- Team B: Three graduate student researchers working on energy storage.
- Team C: Three academic professionals—one in engineering and two in the social sciences—proposing a research project centered on rare-earth minerals.
- Team D: Two graduate student researchers working on developing more equitable electric grid management techniques.
- Team E: Two graduate student researchers working on nature-based solutions for climate resilience.

Majority (83%) of participants indicated that they had prior experience related to energy justice, such as attending workshops, reading literature, or working on projects focused on energy justice. As shown in Fig. 7, 25% of participants identified as Black or African American, 33% of participants identified as Asian, and 42% of participants identified as white. Additionally, 50% of participants identified as women.

4.2 Usability. To understand how usable, or accessible to the target audience, both the JERE Process and tool prototype were for teams, we primarily relied on survey and focus group data collected after the JERE workshops. Participant observation during the JERE

[2]Here, a broad view of the "energy sector" was used, including but not limited to projects or proposals focused on demand- or supply-side energy infrastructure or products, energy resilience, electricity or the electric grid, climate mitigation, improving process efficiency, material discovery related to the energy sector, projects or proposals geared toward U.S. Department of Energy initiatives, relevant software or hardware development, and so on.



Team Project Topics	n	% Selections
Renewables	2	20%
Decarbonization	2	20%
Energy Storage	2	20%
Vehicles and Mobility	1	10%
Buildings, Construction, and Urban Design	1	10%
Non-renewables and Mining	1	10%
Software & Computation	1	10%

Year in Primary Position	n	
1-5 years	8	67%
6-10 years	3	25%
11-15 years	1	8%

Gender	n	
Women	6	50%
Men	6	50%

Where Team is in the Design Process	n	% Teams
Conceptual Design	1	20%
Research & Development	3	60%
Writing a Proposal	1	20%

Age	n	
21-29	6	50%
30-39	3	25%
40-49	2	17%
50-59	1	8%

Prior EJ Experience	n	% Selections
Writing a DEIP (Diversity, Equity, and Inclusion Plan) or CBP (Community Benefits Plan)	4	13%
Writing a "Broader Impacts" Statement for a research proposal	7	22%
Going to a workshop on energy equity or energy justice	6	19%
Reading literature on energy equity or energy justice	9	28%
Doing work focused on energy justice or equity	5	16%
None	1	3%

Fig. 7 Demographics of participants in JERE evaluation study, including their positions, project topic areas, years in their primary positions, their teams' design process progression at the time of the study, their prior energy justice-related experience, and the participants' race, gender, and age distributions

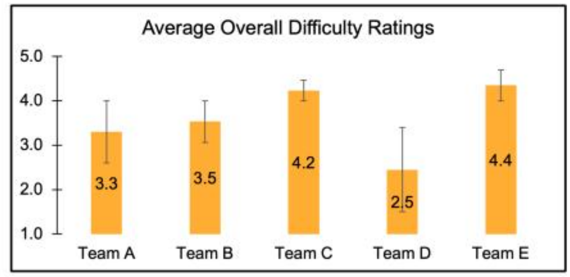
workshops also provided insight into the JERE tool prototype's usability. The post-workshop survey asked participants to rate how difficult they found each stage of the JERE Process and the overall process on a scale from 1 to 5, with 1 being "extremely easy" and 5 being "extremely difficult." As shown in Fig. 8, JERE was generally viewed as a difficult process with the average difficulty rating for the overall JERE Process being 3.59 out of 5.0 and the average difficulty of individual stages of the JERE Process ranging from 3.02 (JERE Stage 1: Initial Assessment) to 3.45 (JERE Stage 3: Distribution-Based Assessment). The entire JERE Process was given a higher difficulty rating on average than the average difficulty of all its stages, with the overall JERE Process being given an average difficulty rating of about 3.6, while the average difficulty rating for all JERE Stages was 3.3.

JERE's perceived difficulty also varied by team. The bar chart in Fig. 8 shows the differences in average overall difficulty ratings for the *entire JERE Process* across teams. Figure 9 illustrates differences in average difficulty ratings for *each stage of JERE* across teams. Of note, Team D had substantially lower difficulty ratings. This team also had the most experience with the kind of sociotechnical thinking JERE aims to encourage, given their

		Overall	Stage 1	Stage 2	Stage 3	Stage 4	Avg. Stages
Team A	P1	4	2	3	5	4.5	3.63
Team A	P2	2.6	2.4	1.9	3.2	2.5	2.50
Team B	P3	4	3.7	3.1	3.9	4	3.68
Team B	P4	2.6	2	3	3	2	2.50
Team B	P5	4	2	4.3	3.8	3.3	3.35
Team C	P6	4.7	4	4	4.1	4.1	4.05
Team C	P7	4	4	4	5	5	4.50
Team C	P8	4	4	4	3.1	3	3.53
Team D	P9	3.4	1.1	3.6	3.6	2.6	2.73
Team D	P10	1.5	1	1	1.5	2	1.38
Team E	P11	4.7	5	4.2	3.2	3.9	4.08
Team E	P12	4	4	3.5	3.5	4.5	3.88
	Average	3.59	3.02	3.33	3.45	3.35	
	STD	0.95	1.33	1.0	0.94	1.03	

1 Extremely Easy — **Extremely Difficult 5**

Averages	Overall	Stage 1	Stage 2	Stage 3	Stage 4
Team A	3.3	2.2	2.5	4.1	3.5
Team B	3.5	2.6	3.5	3.6	3.1
Team C	4.2	4.0	4.0	4.1	4.0
Team D	2.5	1.1	2.3	2.6	2.3
Team E	4.4	4.5	3.9	3.4	4.2



On a scale from 1-5 (with 1 being extremely easy and 5 being extremely difficult), how difficult did you find each portion of the JERE process?

Fig. 8 Participant responses to the question "On a scale from 1–5 (with 1 being 'extremely easy' and 5 being 'extremely difficult'), how difficult did you find each portion of the JERE Process?" The graphic on the left displays each participant's responses—the average difficulty ratings for each participant across each stage of the JERE Process and the averaged difficulty ratings and standard deviations (STD) for the entire JERE Process (Overall) and each of its stages (Stages 1–4). On the right is a table that shows average JERE difficulty ratings across teams, with the average overall JERE rating and standard error portrayed in the bar chart below it.

project area. The supplementary material has additional usability rating comparisons based on (i) access to tools for incorporating justice in participants' work and (ii) profession (graduate students or professionals (section S3.2, available in the Supplemental Materials)).

In addition to these quantitative ratings of JERE's perceived difficulty, participants were provided with a text box to elaborate on their ratings. Two-thirds of respondents elaborated on their ratings. Two participants in two different teams mentioned difficulty understanding wording, terminology, or instructions. Participants also mentioned the issues of there being too much text and too little time to complete the process. One participant stated, "It was hard to understand what to do at each step, particularly when it came to revisiting Sec. 1 [JERE Stage 1] and identifying or filling gaps. Some of the terminology was difficult to understand, but that's probably because there wasn't sufficient time in the testing sessions." A participant also mentioned that JERE may be too extensive to apply to more complex projects with different disciplines and perspectives. The participant stated, "The level of detail here is great, but completing even a portion of this process (and taking it seriously) will take a lot of time, especially if the team has different disciplines and perspectives represented. That conversation is important, but I'm not sure how realistic it is for a team to do this."

Those who found JERE most difficult often noted that it was thought-provoking. A participant mentioned difficulty applying JERE at early stages (e.g., the proposal phase) of a project, saying, "I found it very thought-provoking but difficult to apply

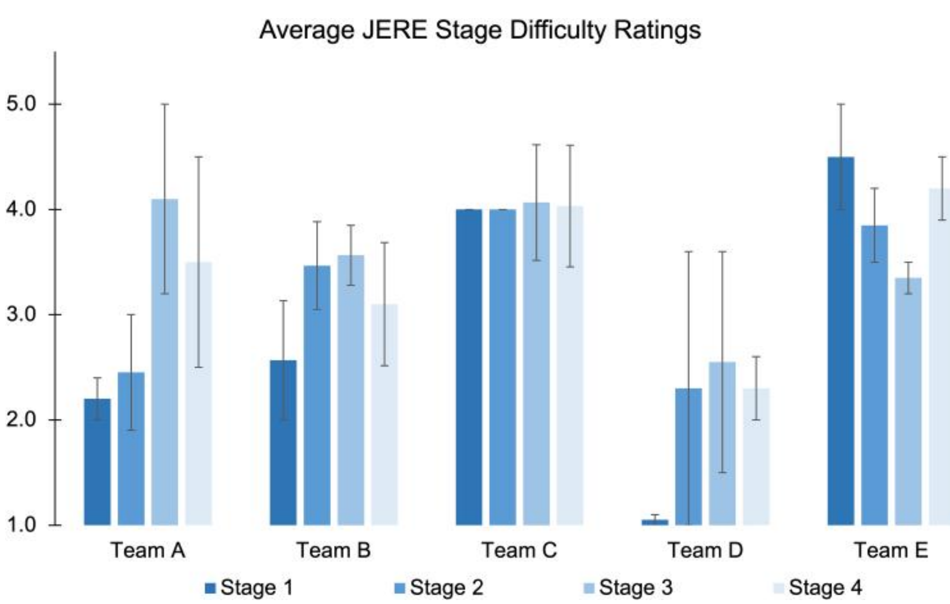


Fig. 9 Averaged team responses to the question "On a scale from 1–5 (with 1 being 'extremely easy' and 5 being 'extremely difficult'), how difficult did you find each portion of the JERE process?" The error bars show standard error.

to our project at this very early stage when we know so little. But it gave us lots of things to think about and helped us determine some important considerations that we hadn't thought about to date." Others found JERE's difficulty to be milder. For example, one participant wrote, "I'm not sure that it is difficult but it does allow you to think through your project very deeply which is great but not easy or quick." Both those who found JERE difficult (ratings: >4) and those who did not find it to be too difficult (ratings: <4) mentioned JERE being a long process. The theme of JERE's length came up multiple times throughout the study and will be discussed in more detail when investigating JERE's appeal in Sec. 4.4.

Along with survey responses, feedback provided during team focus group sessions at the end of the study also provided useful insight into how participants perceived JERE's usability. The major findings from the focus groups surrounding JERE's usability were that participants desired more feedback and guidance, clearer instructions, and found facilitation helpful throughout the process. One participant stated:

> "Although I know there is a ton of flexibility in how the tool is used. There is sometimes, I was thinking like, I'm not sure if we are using it the 'right way,' even though maybe there isn't a right way and maybe that's the point. But there were some times where it was, I was confused about what exactly I needed to do."

Participants from other teams also indicated a desire for clearer guidance, especially when it came to the use of energy justice terminology.

During participant observation, it also appeared that it took participants time to adjust to the new way of thinking JERE begot. During the focus group session for Team B, one participant said, "It's definitely a different way of thinking and hard to switch my brain over, but once it's over there, we got it." Additionally, during participant observation, it was noted that large walls of text were often skipped over.

4.3 Impact. Because "impact" here is defined as meaningfully influencing design decision-making and processes, participant changes in thought processes or comfort with applying energy justice principles to their work were used as the main indicators of impact. These indicators primarily came from survey data. More specifically, we analyzed differences in responses to nine statements (shortened representation of statement in parentheses):

(1) I am familiar with energy justice. (**Familiarity**)
(2) I feel comfortable discussing energy justice, broadly. (**Broadly**)
(3) I feel comfortable discussing energy justice as it pertains to my field, specifically. (**Field**)
(4) I feel comfortable applying energy justice to my work. (**In Work**)
(5) Energy justice is important in my work. (**Important**)
(6) I can identify problems related to energy justice in my work. (**Problems**)
(7) I can identify solutions to energy justice-related problems in my work. (**Solutions**)
(8) I have experience applying environmental considerations to my work. (**Environmental**)
(9) I have experience applying social considerations outside of justice to my work (e.g., economic, behavioral, etc. considerations) (**Other Social**)

Participants were asked to note the extent to which they agreed or disagreed with each statement in surveys both before and after the JERE workshops. Options included "Agree," "Somewhat Agree," "Neither Agree nor Disagree," "Somewhat Disagree," and "Disagree." Because most of the survey data were ordinal or categorical, numerical representations of participant responses, or changes to their responses, were used to assess impact—namely frequency data, means, medians, and variance values. We did not seek to identify statistically significant changes given the lack of continuous data collected and the study's small sample size.

Numerical representations were also provided for each option, ranging from +2 for "Agree" to −2 for "Disagree" with "Neither Agree nor Disagree" being 0. The change in responses between participants' pre- and post-workshop responses was used as an indication of JERE's impact. If participants went from a lower level of agreement to higher one, it was labeled as an "advancement." For example, if they went from "Somewhat Agree" to "Agree," the numerical representation would increase by 1, from +1 to +2. When a participant indicated a lower level of agreement, for example, going from "Neither Agree nor Disagree" to "Disagree," this would be labeled a "decline" and numerically represented as $\Delta = -2$.

To get a sense of all the overall changes in sentiment among participants before and after the JERE workshops, we looked at the changes in numerical representation and provided summary statistics for those changes. Average and median change in sentiment were used as indicators of sentiment change across all participants, while the variance of the change provides an indication of how disparate sentiment changes were among the participants. The individual and overarching changes in sentiment for each statement are portrayed in the supplementary information (section S3.3, available in the Supplemental Materials). A summary of the data is provided in Table 2.

The most distinct change in responses observed pre- and post-JERE workshops overall was to the statement: "I can identify solutions to energy justice-related problems in my work." Seven participants indicated advancement in this area. The area of most decline was in experience applying environmental considerations to their work—an area JERE did not particularly focus on. The least variance among participants was around the statement "Energy justice is important in my work," and the least change in response from pre- to post-workshops was around the statements "I can identify problems related to energy justice in my work" and "I have experience applying social considerations outside of justice to my work (e.g., economic, behavioral, etc. considerations)."

Table 2 The aggregated changes in participants' agreement to the nine statements used to assess JERE's impact

	Familiarity	Broadly	Field	In Work	Important	Problems	Solutions	Environmental	Other Social
Advancement	4	3	4	3	1	3	7	2	2
Decline	2	1	2	1	2	0	1	4	1
Same	6	8	6	7	8	9	4	5	9
Missing Response	0	0	0	1	1	0	0	1	0
Average Δ	0.17	0.08	0	0.09	-0.09	0.33	0.58	-0.45	0
Median Δ	0	0	0	0	0	0	1	0	0
Variance Δ	0.97	1.24	1.17	0.63	0.26	0.39	1.08	1.34	0.50

Note: The rows labeled "advancement," "decline," and "same" represent the number of participants who agreed more, disagreed more, or saw no change in sentiment pre- and post-study, respectively. Of all statements, the most distinct change in responses observed pre- and post-JERE workshops overall was to the statement: "I can identify solutions to energy justice-related problems in my work." Highlighted cells represent the highest value(s) in the given row, except for the last row, in which the highlighted cell is the lowest variance of numerical representations of participants' agreement to the nine statements.

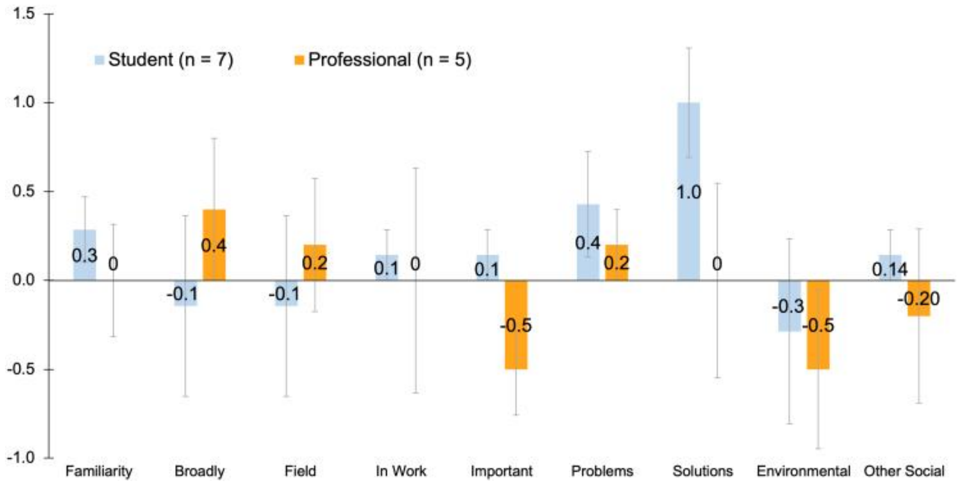


Fig. 10 Average numerical representations of sentiment change from pre- and post-JERE workshops for both students and professionals. Error bars represent standard error. The numerical representation of participants' sentiment change can be positive (advancement) or negative (decline).

Similar to general environmental considerations, the latter was also an area JERE did not particularly focus on.

As displayed in Fig. 10, students generally demonstrated more perceived impact from participating in JERE workshops than the professional participants. The starkest contrast between these two groups was around indicated changes in their perceived ability to identify solutions to energy justice-related problems. Whereas students on average saw the most advancement in that area, professionals on average saw no change.

During focus group sessions, participants also indicated that using JERE could be impactful in their work or field. One participant highlighted this perception by saying, "I'm really looking forward to seeing you develop this tool past the pilot and past your dissertation. And I think it has potential to be, you know, really transformative for, and to help create, you know, multidisciplinary teams that really take both the technical and the social really seriously." Yet, this potential impact can only be realized if there is broader uptake of the JERE Process, and that requires users to both see value in it as a method and be willing to use it. These elements of JERE were assessed using survey and focus group data and are described in detail in the subsequent section.

4.4 Appeal. To assess appeal, we sought any indications of interest or disinterest and observed ways participants discussed JERE's value or lack thereof. In the post-JERE workshop survey, participants were asked to select the most helpful (Fig. 11(*a*)) and least helpful (Fig. 11(*b*)) stages of the JERE Process. The seemingly most helpful stage of JERE, by a small margin, was JERE Stage 4, the Requirements Translation Stage, as shown in Fig. 11(*a*). Similarly, the seemingly least helpful stage of the JERE Process was JERE Stage 3, the stage in which participants revisited the Distribution-Based Assessment, as shown in Fig. 11(*b*). Because perception of the JERE stages that are most and least helpful can depend on the team, both Figs. 11(*a*) and 11(*b*) display agreement across entire teams in yellow.

Aside from how helpful each stage of JERE felt to participants, JERE's appeal was also assessed according to participants' agreement with the following four statements:

(1) this workshop was a valuable use of my time.
(2) I would recommend this workshop to colleagues in my field.
(3) I would use JERE again.
(4) I would recommend JERE to a colleague.

As portrayed in Fig. 12(*a*), 83% of participants agreed with the statement "Attending this workshop was a valuable use of my time"; 67% of participants agreed with the statement "I would recommend this workshop to colleagues in my field"; 58% and half of the participants agreed with the statements "I would use JERE again" and "I would recommend JERE to a colleague," respectively. As seen previously, students generally had a more favorable view of JERE than professional participants. On average, JERE appears to have been more appealing to students, as shown in Fig. 12(*b*). Although professionals indicated that the workshop was valuable, they were less likely to engage with it again, on average, or recommend it to colleagues, especially if they were not engineers (two-fifth professional participants were not engineers).

A common point of feedback, especially from professional participants, was that the JERE Process was too long or there was not enough time allotted in the workshop to complete it. Some participants also noted that the length of time needed to complete JERE may be unrealistic for teams, particularly teams working on large, multi-faceted, and complex problems.

The most common theme to arise from focus group sessions centered JERE's ability to act as a thought-provoking process helpful for surfacing important considerations, providing participants with a broader view of their work, highlighting gaps in their work they may not have considered, providing useful reminders, and encouraging a new way of thinking. Some participants noted that these conversations were important to have. One of the social scientists on Team C spoke to this point.

> "I think one thing that we saw it do is identify some of the gaps in the way that we tried to approach justice in the current project and that, you know, I think I spent a lot of time thinking about this stuff, but we didn't necessarily identify or at least even discuss how to make sure that the justice work or the social science that gets done as part of this project actually informs the engineering work and vice versa. So, I think that exercise is important."

Participants also highlighted the benefit of having a structured process to systematically consider justice and bridge sociotechnical factors in their work, mentioning JERE's ability to translate between traditional engineering and social sciences considerations. For example, one graduate student researcher in engineering from Team D stated:

> "I like having a framework … to have the thoughts be put into specific boxes. And using like … more of a conventional engineering requirements process to assess a social concept and how they relate to something technical. It's helpful to kind of like bridge that gap between … rigid thinking of engineering with the … seemingly loose way that social sciences think about these types of justice issues."

(a)

JERE Stage - Most Helpful	Count	Participant %
Initial Assessment	6	50%
Process Planning and Pursuit	6	50%
Distribution-Based Assessment	6	50%
Requirements Translation	7	58%
Other*	1	8%

*Comment: "I found the overall flow helpful, but parts were repeated so I have a hard time placing which things was in which place"

(b)

JERE Stage - Least Helpful	Count	Participant %
Initial Assessment	1	8%
Process Planning and Pursuit	2	17%
Distribution-Based Assessment	5	42%
Requirements Translation	3	25%
Other*	3	25%

*Comment: Two participants stated "N/A." One stated "I found the overall flow helpful, but parts were repeated so I have a hard time placing which things was in which place"

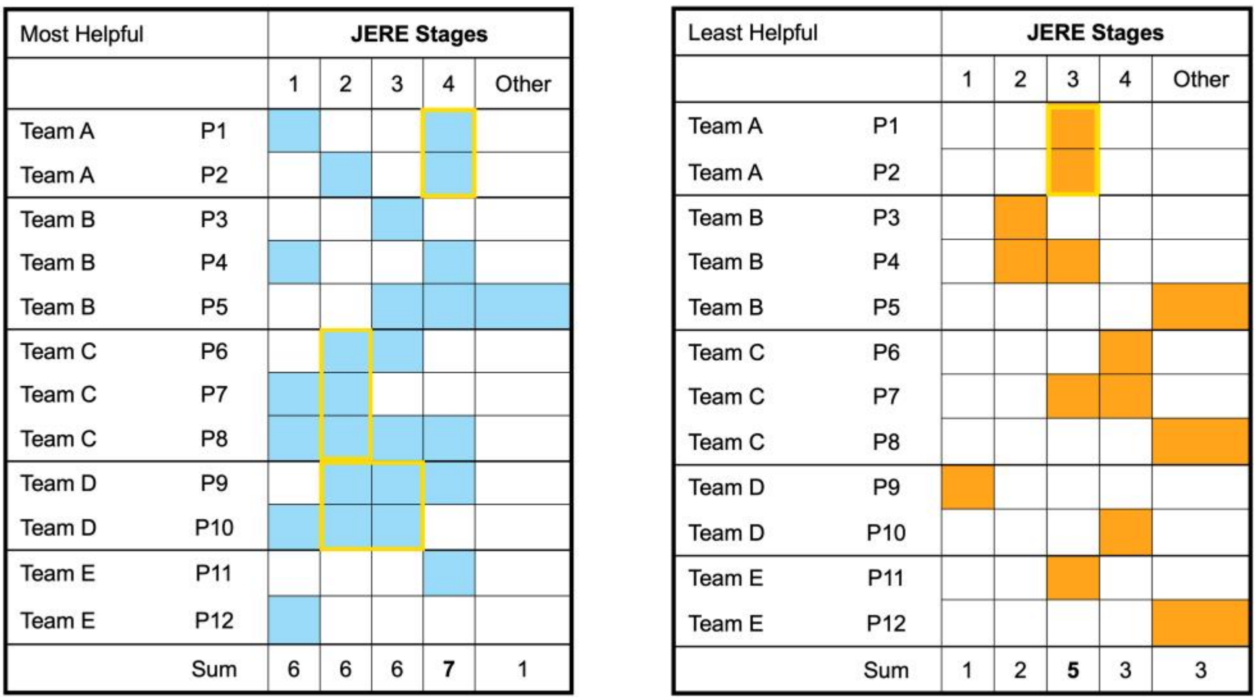


Fig. 11 (*a*) Participant selections of the most helpful stages of the JERE Process. JERE Stage 4, the Requirements Translation Stage, was selected the most times. Outlined boxes signify where entire teams agreed about the most helpful stages. (*b*) Participant selections of the least helpful stages of the JERE Process. JERE Stage 3, the stage in which participants revisited the Distribution-Based Assessment, was selected the most times. Outlined boxes signify where entire teams agreed about the least helpful stages.

Even with the positive feedback, some participants felt that the JERE tool was at too rudimentary a stage to recommend, with one member of Team C saying, "I would love to see how this progresses and how the tool improves, and I would likely recommend it once it's at a more advanced stage, and to particular types of teams."

4.5 Engaging With JERE. This study's fourth research question sought to understand when and how engineers would engage with JERE. The main source of information used to answer this research question was participant responses to the focus group questions. When asked if they could imagine themselves going through the JERE Process again in the future, and if so, under which circumstances they would use it, participants envisioned engaging with JERE again in six scenarios:

(1) Implementing JERE in early project stages;
(2) Using JERE during commercialization;
(3) Using JERE to bolster non-engineering activities;
(4) Using JERE for smaller, more specific projects;
(5) Using JERE in the same way as it was presented in the workshops for their projects; and
(6) Using JERE as an educational tool.

(1) *Implementing JERE in early project stages*: Participants imagined JERE used in project planning, scoping, brainstorming, and for project proposal development. Some participants indicated not using JERE at later stages, when the project is in a more finalized state.
(2) *Using JERE during commercialization*: A Participant in Team B envisioned using JERE when considering commercializing the technology they are developing, saying "Yeah, I'd definitely use it if my technology were to be commercialized, especially. Useful to think about beforehand, but I think like necessary at that point."
(3) *Using JERE to bolster non-engineering activities*: When participants discussed using JERE, they often mentioned activities or areas outside of engineering, such as workforce development, community engagement, and public policy.
(4) *Using JERE for smaller, more specific projects:* Participants indicated that JERE would be easier to apply to smaller, less

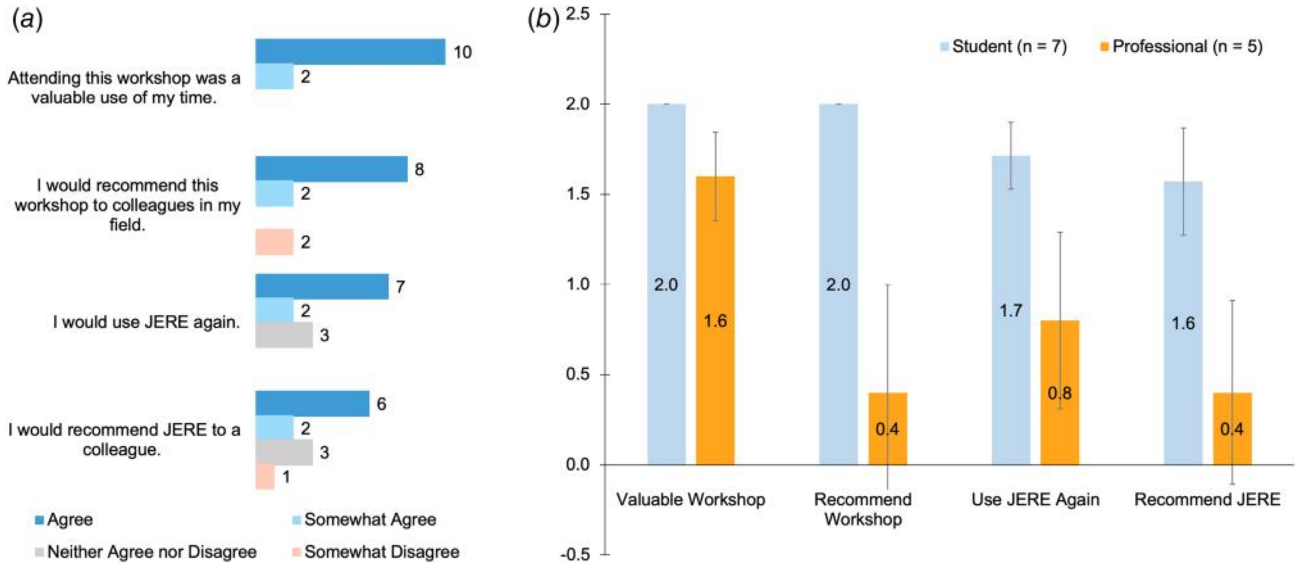


Fig. 12 (*a*) All participant responses to statements signifying the value or appeal of the JERE Process and workshop broken down by percentage. (*b*) Table comparing the average numerical representations of JERE's value and appeal to both students and professionals. Here, 2 = "Agree," 1 = "Somewhat Agree," 0 = "Neither Agree nor Disagree," −1 = "Somewhat Disagree," and −2 = "Disagree."

complex projects, especially once engineers and researchers have a preliminary understanding of the groups who may be impacted by their work.

(5) *Using JERE in the same way as it was presented in the workshops for their projects*: Some participants indicated they would use JERE in the same way it was presented during the workshop—working through each stage of JERE while focused on a particular project.

(6) *Using JERE as an educational opportunity*: Participants also highlighted JERE's potential to act as an educational tool through mini-courses or as a module in a course.

Additional quotations from participants that exemplify these six scenarios and further detail feedback from participants can be found in the supplementary materials (sections S3.4 and S3.5, available in the Supplemental Materials, respectively).

4.6 Participant Feedback and Recommendations. Participants provided many suggested improvements for the JERE workshop, process, and tool prototype, some of which have already been discussed. These improvements fell into three overarching categories:

- JERE tool-focused feedback and recommendations;
- JERE workshop-focused feedback and recommendations;
- JERE Process-focused feedback and recommendations.

(1) JERE tool-focused feedback and recommendations

Participants gave feedback on ways to improve the JERE tool prototype, including requests to:

(i) Enable more automated components through artificial intelligence-enabled technologies like chatbots to provide feedback and guidance to JERE users: A graduate researcher suggested an "automated component" to "interact with you and give you suggestions like 'oh, we recommend this; or have you considered this?' given like the details that you put into the program." A professional researcher also recommended that artificial intelligence or chatbots would improve the tool by providing a summarized conclusion of findings or outcomes.

(ii) Provide more information to preempt each section of the JERE Process: Given JERE's length, some participants wanted more insight into the next section of the JERE tool to ensure they did not preemptively input data into the wrong sections. This issue also points to potential redundancy in the JERE tool.

(iii) Adjust JERE or create a version of it to help with writing proposals: A professional participant on Team C highlighted the need for a shorter or simplified version of JERE, especially for researchers developing proposals.

(2) JERE workshop-focused feedback and recommendations

In terms of improving the JERE workshops specifically, participants mentioned wanting the workshops broken down, shortened, and simplified with more time between major stages of JERE. There were more conflicting opinions from participants when it came to familiarizing participants with the JERE Process during the workshop. One participant mentioned wanting more of an overview at each phase while a participant on another team only wanted to be oriented to the process once.

(3) JERE process-focused feedback and recommendations

The major process-focused recommendations highlighted a need for clearer instructions or guidance in the JERE Process and a need for more substantive conclusions to the process. During participant observation, many participants asked clarifying questions about definitions for "considerations" versus "requirements" and "stakeholders," so there appears to be a need to provide users with clarity about what is meant when thinking through these terms. Broad definitions were provided, but from prior studies, it appears users may benefit from both facilitation and guidance, and concrete examples [7].

Finally, two professional participants from different teams also noted a desire for the JERE process to provide them with a more concrete plan or a synthesized summary of their work. One participant stated, "I actually don't have a problem with it taking four hours. I mean, if we were gonna put together a project, I would wanna spend at least four hours talking about these elements… but I think at the end of that four hours I would like for it to generate like a pretty explicit plan for a project…"

From reviewing these results alongside the initial project descriptions, identified knowledge gaps, and final requirements teams noted in the JERE tool prototype, JERE appeared to change team thinking, key considerations, and prompted new conversations about the process for achieving their projects' goals, yet the key project requirements often did not change substantially at the end of the process. Because this study did not collect an initial list of requirements, a direct comparison could not be made, but two groups highlighted safety in their list of final requirements, one group highlighted avoiding "exploitatively extracted materials, verified by government and industry," and four of five teams had requirements that centered end-users or industry operators (two teams focused on community groups along with industry workers or operators). Additionally, all groups identified gaps, but none had the time to actively fill those gaps, a major limitation of the study, which may explain the lack of change in requirements.

All of these recommendations, factors of usability, appeal, impact, and opportunities for engagement, informed the updated version of the JERE Process described in the subsequent section and available in section S1, available in the Supplemental Materials. This feedback can continue to inform future versions of the JERE Process, tool, and workshops.

5 Discussion

The JERE Process can provide engineers with a step-by-step guide to incorporate justice considerations into their technical design process. JERE was made to be applied early in the engineering design process as design requirements are created. Similar values-based requirement engineering techniques have also been found in software development [37,38], which indicates that although built for energy engineers, JERE may also be used for systems or projects outside of the energy sector or potentially applied in other technology development processes, such as the software development process.

Yet, JERE is not without its limitations. The JERE Process is intensive and time-consuming, particularly for teams that have never engaged with the sociotechnical aspects of their work or to whom sociotechnical elements are completely foreign. Overall, the JERE tool prototype was seen as relatively difficult to use due to its multiple parts, reliance on vocabulary from energy justice literature, reliance on text, and the length of the process and workshops. Additionally, it is up to the project team to decide the extent to which they want to engage with JERE and to what ends, meaning that it can be used to superficially engage with justice considerations rather than doing so more purposefully. Despite these drawbacks, JERE elicited helpful conversations among project teams and highlighted aspects of their project that were oftentimes forgotten or overlooked. It also provided a structure for more systematic engagement with justice considerations and reinforced that individuals could orient their technical projects toward more just outcomes.

Study participants recommended several improvements to the JERE Process and tool. A major recommendation was around simplification. Participants sought both simpler terminology and a simpler, shorter process. One team that used JERE for a U.S. Department of Energy proposal recommended a version of JERE that could be used for project proposals, specifically. In addition to a shorter process, many participants indicated wanting more time to complete the process. Participants also provided recommendations surrounding the JERE tool prototype's user interface and integration. They recommended more advanced user interfaces with multimedia, automation, and potential artificial intelligence integration to provide users with additional guidance and feedback.

Table 3 Table demonstrating the final state of the JERE tool prototype post workshops

	Filled fields	Priority	Important	Remove consideration	Fill gap
Team A	17%	9	1	12	9
Team B	18%	15	0	18	2
Team C	13%	9	0	4	34
Team D	16%	10	1	0	12
Team E	13%	15	2	0	8

Note: The table includes the percentage of all JERE fields filled, the number of considerations marked as priority, important, and to be removed, and the number of considerations with gaps to fill. The JERE prototype enabled users to easily skip sections by design. The low percentage of filled fields shows that, on average, participants left 85% of fields blank.

Although JERE was made for users to be able to easily skip and return to sections, the presence of a section compelled users to address it. This limitation was particularly apparent because the tool used to build the JERE prototype did not allow for any dynamic expansion of options, meaning only the maximum number of spaces for user responses could be set. In Table 3, the first column shows that the percentage of filled fields (number of filled fields/maximum potential number of fields) is less than 20 for all teams. This shows that the maximum number of potential fields or considerations the tool allowed participants to use exceeded their usage by over 80% across the board. With such a large number of "blank" spaces, users likely felt their use of the tool was incomplete. That, coupled with the limited time of the workshops, made timing and the feeling of "completion" a problem across the board.

More exposure to the type of sociotechnical thinking JERE elicits may make going through the process easier. For example, Team D had the most exposure to this kind of thinking and found the process to be substantially easier. Additionally, it was noted during participant observation that it took time for participants to become more accustomed to thinking about broader considerations in their work.

JERE was built with the customs of engineers in mind—leading to a more structured and guided step-by-step protocol to follow. Due to the exclusive focus on engineers, there was no focus on the customs of other disciplines, which may explain the lower overall appeal JERE had to social scientists. This discrepancy emphasizes a need for JERE to better consider other disciplinary practices and more holistically foster interdisciplinary teamwork.

Additionally, it is worth noting the differences between graduate student researchers and professionals when it came to JERE's appeal and perceived impact. JERE appeared to be more appealing and impactful for graduate student researchers than professional researchers. There could be a few reasons for this. One potential reason is that all the student researchers involved were engineers, and this design intervention was explicitly built for engineers, making the process less readily adaptable for non-engineers or more interdisciplinary teams. Almost half of the professional participants were social scientists. Additionally, studies have shown that design experts take more time in problem scoping [39,40], so the additional time JERE warrants may seem untenable. On the other hand, one team of professionals saw the JERE Process as a helpful, structured brainstorming activity, which could aid professionals in the process of problem scoping and identifying relevant information to gather. Since experts have been seen as having more of a solution-focused than a problem-focused approach, it is possible JERE spends too much time problematizing justice issues [40].

Years of experience and solidified ways of working may make professionals less willing to change their working styles, especially given existing responsibilities, an underdeveloped JERE prototype, and a lack of time. More experienced designers may also be confident in their awareness of their work's limitations or believe they understand the necessary dimensions for success [41], and they may thus see an intervention like JERE as unnecessary. In such cases, they may find more straightforward, question-based interventions about the potential social justice implications of their work helpful [17,30,31,33].

JERE was created to address gaps related to context, accessibility, and perceived responsibility of energy engineers regarding

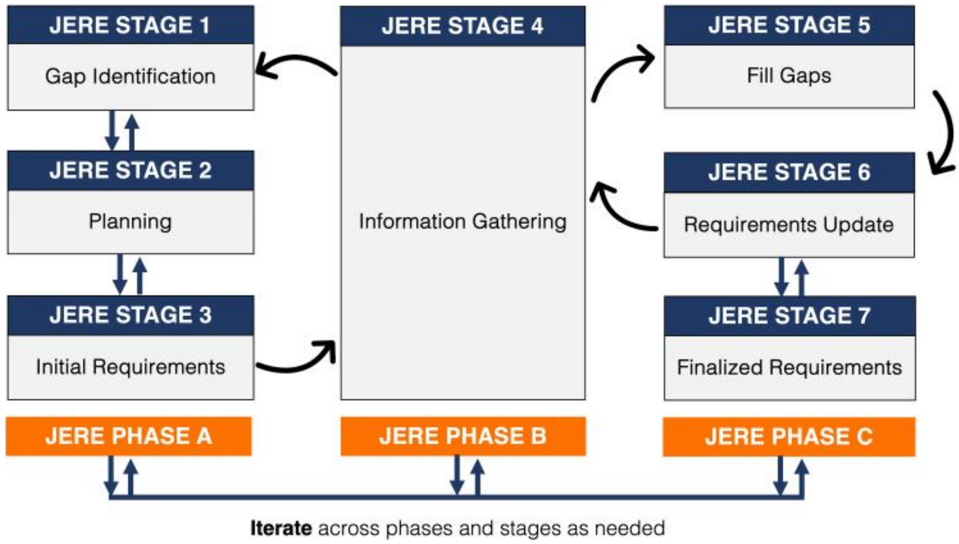


Fig. 13 An overview of the updated JERE Process based on the feedback obtained through intervention evaluation. Here, JERE Stage 1, and potentially Stage 2, can be used by teams writing proposals for new projects.

embedding energy justice in their work. We tackled the context gap by building the JERE Process with a focus on a technical audience in energy, climate, and sustainability. One drawback with this focused design approach is that it may have caused JERE to be less effective for members of project teams outside of the key demographic. Similar to limitations researchers have seen in universal design, all products will face the paradox of not being able to meet the needs of every user, and a design intervention is no exception [23]. JERE was designed with a step-by-step guided structure to make it more accessible to technical energy practitioners. Mattson et al. show that providing needed structure and prompts aligns with higher-quality ideas from designers [30]. Yet, although thought-provoking, the original JERE Process and terminology were found to be difficult to navigate and potentially too detailed depending on where a team was in their project. For higher-level guidance, these teams may find question or list-based interventions more accessible [17,31,33]. Finally, JERE was designed to place energy justice in the purview of energy engineers, researchers, and practitioners in order to bolster alignment with systems justice principles, similar to other interventions with the goals of promoting a just energy transition [14,33].

5.1 An Updated JERE Process. We updated the JERE Process based on the results of this evaluation study, and the new version of JERE is portrayed in Fig. 13. A guide for the updated version of the JERE Process is available for readers to apply in section S1, available in the Supplemental Materials (https://github.com/bettinark/JERE/blob/main/JERE Article Supplementary.pdf). The process is now broken into three iterative phases (Phases A, B, and C). The first phase of JERE consists of three stages, the second phase of JERE consists entirely of information-gathering, and the last phase of JERE also consists of three stages. The updated JERE Process starts with gap identification, which consists of a consolidated version of the Distribution-Based Assessment. Instead of considering the same factors across different levels—such as benefits and burdens across primary, secondary, and tertiary groups—users are prompted to consider only one (the first) level and given the option to consider others if they would like, allowing greater flexibility in gap identification. As shown in Table 3, the "Important" categorization was underutilized; thus, we removed it, leaving users with "priority" and "fill gap" options.

The second stage of the updated version of JERE involves creating an information-gathering protocol, which includes identifying equity-centered frameworks and data collection methods, and developing the project's decision-making and communication protocols. It consists only of the second ("Information-Gathering Protocol") and third ("Decision-Making & Communication Protocol") steps of the original JERE Process. Actual information-gathering is now moved into the second phase of JERE (Phase B). JERE Stages 1 and 2 are the portions of the new process that teams can use when they are proposing new projects. At the end of JERE Phase A, users should have their initial requirements.

Information-gathering in JERE Phase B is inherently an iterative process, which allows users to return to Phase A as they see fit and continue to Phase C when they are ready. Similar to the original JERE Process, JERE Stage 5 is dedicated to revisiting the consolidated Distribution-Based Assessment and filling any noted gaps that users planned to fill. Users are provided the same resources for benefit optimization, burden mitigation, and understanding tensions and tradeoffs. They then use this information to iteratively update their system requirements and specifications until they have a finalized list of requirements. These shorter, simplified phases of JERE should allow teams to collaboratively plan, gather information needed to better understand the justice implications of their projects, and decide what changes they would like to make as they learn more.

5.2 Study Limitations. There were four major limitations of this study. The first major limitation was its short time span. Assessing the true impact of this design intervention would require a longer, potentially longitudinal, study to observe JERE's application in a project and the outcomes of that application on both system requirements and the creation and deployment of that system. Since participants only made requirements at the end of the original JERE Process, we could not compare these requirements to other iterations of requirements. Additionally, time limitations did not enable us to test the updated version of the JERE Process. The second major limitation was the small participant sample size. This study was designed to be more of a case study, but a larger follow-on study with the updated JERE Process and an updated tool could provide more robust, statistically significant results. Additionally, using the rudimentary JERE tool prototype to assess the JERE Process links the two, making it difficult to separate opinions and impacts associated with the process versus the tool. Is it the

JERE Process itself that is long and cognitively burdensome, or is it the way the process was laid out in the prototype?

Another potential limitation inherent in observational studies is the effect of the observer. During a focus group session, one participant said, "It does seem like, I feel like it would be really hard to be you, like the moderator, like the facilitator of this. I feel like every time we were talking about something I was like, I bet [Facilitator] is like screaming in her head what we should just say based off of what we've already said because she knows." This statement emphasizes the awareness participants had of being observed, which may have changed their behavior or engagement with the tool and process.

6 Conclusion

Systems justice calls for a collective response to existing problems of injustice. Although most participants were researchers, through this article and the introduction of JERE, we aim to encourage energy engineers, developers, and practitioners to reconsider, reevaluate, and adjust their work to better position it in the pursuit of a more just energy system. JERE can be applied during project proposals, as teams brainstorm or plan projects, or may be useful for energy developers as they decide on where to site projects and populations to engage. As demonstrated by Lavi and Reich (2024), values embedded and reinforced by the systems we create and fortify are complex, multidimensional, and ever-evolving [42]. Interdisciplinary teams and continuous reexamination of system values allow for more in-depth engagement with JERE and the justice principles it aims to embed in technical work.

The majority (83%) of participants indicated that they had prior experience related to energy justice, such as attending workshops, reading literature, or working on projects focused on energy justice. Yet, JERE was viewed as challenging given the length of the process, text-heavy concept introductions, ambiguity in definitions, and uncertainty at the end of the process, as participants felt they lacked very concrete next steps. Participants viewed JERE as a valuable tool for brainstorming, thinking more holistically about their projects by surfacing under-examined areas, and providing an educational opportunity. Overall, JERE was found to be more usable, impactful, and appealing to graduate student researchers, and even more so for student researchers with some experience working at the intersections of technology and equity or justice.

Study participants recommended several improvements to the JERE Process and tool, including shortening and simplifying the process, adding a more advanced user interface, integrating artificial intelligence, and providing additional guidance and clarity in the process. Based on the findings from this study, an updated version of the JERE Process was introduced to allow users to more easily engage with JERE and better understand and steer the justice implications of their work. Since carrying out this study, there has been a rapid progression and deployment of public-facing large-language models (LLMs) and artificial intelligence-based programs. Now, similar to suggestions participants gave, users can essentially upload the JERE Process guide into an LLM-based program and more dynamically engage with it.[3] Given JERE is a newly developed process, there will need to be a more rigorous evaluation of it as a tool, especially in its updated form or with updated application of JERE.

We encourage researchers to continue evaluating and updating JERE and similar processes to embed principles of justice in technology development, especially as we find ourselves at a technological epoch given impending changes in climate, artificial intelligence, and energy. It is important to acknowledge that as we are writing this paper in 2025, the political landscape in the United States has drastically shifted, with an administration actively dismantling and discouraging just transition work, among other important research topics. Such systematic dismantling makes it both challenging for researchers to pursue this work and especially important to continue embedding justice principles in the technology that will fuel future communities and economies.

This work highlights points of difficulty that engineers and researchers may face when attempting to practically embed justice principles in their design work, along with the practical difficulties designers may have attempting to build and deploy tools to enable engineers and researchers to do this embedding. It also demonstrates the benefits of engaging with dimensions of justice early in the design process and lays the foundation for others attempting to ensure technical solutions can support goals toward a just energy transition. As justice considerations play more of a central role in the energy transition, these findings can help to improve energy researchers' and engineers' engagement with the potential justice implications of their work and more consistently keep the needs, assets, and priorities of frontline communities centralized in that work. Realizing a more just and equitable future energy system requires a reimagining of our work as engineers; it will also call for enhanced engagement with frontline communities and a deeper respect for the knowledge, innovation, rich histories, and creativity members of frontline communities possess.

[3]We acknowledge the host of issues—from the development, deployment, and use of LLMs—present in many popular LLMs, but the nuanced discussion of AI in pursuit of (energy) justice or more just technology development would warrant an article of its own. For further engagement with these topics, we recommend looking to the works of authors such as Dr. Ruha Benjamin, Dr. Joy Buolamwini and the Algorithmic Justice League, and Dr. Timnit Gebru and the Distributed AI Research Institute.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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