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Commentary

JUST-R metrics for considering energy justice in early-stage energy research

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Introduction

Achieving sustainable decarbonization of the energy sector requires implementing and improving energy technologies while simultaneously managing sources of social inequity in the energy system. Centering energy justice, which has "the goal of achieving equity in both the social and economic participation in the energy system, while also remediating social, economic, and health burdens on those historically harmed by the energy system," [1] in the transition to clean energy has become an increasingly urgent priority for social scientists, policymakers, and community activists alike. However, late-stage consideration of social impacts of energy technologies may result in identifying inequities only after substantial time, money, and effort

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have been expended on research and development (R&D). This issue is exemplified by concerns over environmental and human health impacts related to cobalt in lithium-ion batteries,[2] which has spurred research into alternatives only after decades of R&D and the establishment of supply chains, infrastructure, and markets for cobalt-containing chemistries. Other examples include issues with land use and resource consumption related to first-generation biofuel feedstocks as well as occupational hazards and pollution associated with photovoltaics manufacturing.[2] In all these cases, subsequent R&D to improve technologies or processes cannot undo the effects already experienced.

Incorporating energy justice from the earliest stage of R&D will enable more just technology implementation, but integrating justice considerations into early-stage research is a challenge due to a lack of tools to assess and manage them. To fill this gap, we center early-stage research to develop the Justice Underpinning Science and Technology Research (JUST-R) metrics framework—energy justice metrics specifically targeted at early-stage researchers to assess their work on an immediate timescale. By applying these metrics to a case study focused on materials for next-generation photovoltaics, we highlight potential benefits and barriers to implementing this framework in early-stage research and discuss necessary institutional and individual actions needed for researchers to effectively leverage the tool to incorporate justice-focused criteria into R&D decision making.

JUST-R metrics framework for energy justice in R&D

The JUST-R framework includes 30 metrics from literature and 20 new metrics proposed to fill gaps in applicability to early-stage energy research. The framework is organized along three axes: responsible research and innovation (RRI) dimensions, tenets of energy justice, and technology readiness levels (TRLs).

RRI examines social impacts of research processes through four dimensions: anticipation (identification of risks and potential impacts), reflexivity (sociotechnical integration and interdisciplinarity), inclusion (public and stakeholder engagement), and responsiveness (ability to respond to ethical and societal aspects).[3] These place metrics in the context of socially guided R&D and are generally applicable across research stages. However, RRI's process-oriented approach alone is insufficient, as energy justice seeks to achieve specific outcomes related to equitable participation in the energy system. To prioritize these outcomes, we also leverage four tenets of energy justice: distributional (how benefits, burdens, and responsibilities of the energy system are distributed across a population), recognition-based (identification of groups who have been ignored, misrepresented, or negatively impacted by the energy system), procedural (equitable engagement that promotes access, transparency, and fairness in decision making and other processes), and cosmopolitan (considering impacts of broader externalities of energy technologies or systems).[1] By leveraging RRI and tenets of justice together, the JUST-R framework considers both research processes and energy justice impacts to better connect early-stage decisions to long-term outcomes.

TRLs, which measure the maturity of technologies under development,[4] organize metrics along stages from basic science (TRL 1) to technology demonstration (TRL 9). Justice-related metrics from literature are preferentially applicable to high TRLs, when technologies are close to deployment, leaving critical gaps for early-stage research. To address this limitation, five themes are identified to fill the gaps and 20 new metrics proposed within them. Further details on framework and metrics development are available in the supplemental information.

Overall, the JUST-R framework recommends 40 metrics for each research stage; Figure 1 maps their distribution for TRL 1, with full metrics for all TRLs given in Tables S1–S5. The metrics span every RRI dimension and tenet of justice, exemplifying the comprehensive nature of the JUST-R framework. Figure 2 lists all metrics for TRL 1 in full,[5–8] categorized by tenets of justice. Of these, 20 metrics are newly proposed in this work (bold in Figure 2) to address the five themes relating to gaps identified in applicability to early-stage research.

Theme 1. Hidden process costs

These metrics deal with costs or savings associated with the research life cycle but not necessarily paid by the research budget. This spans costs incurred, for instance in managing hazardous waste, and costs reduced, as in development of more energy-efficient lab processes. Assessing "hidden" costs enables fairer comparison of cradle-to-grave costs of emerging technologies with those of competing technologies, shedding light on whether potential savings in operation may be worthwhile. Moreover, analyzing different segments of the research life cycle independently gives insight into how costs may be distributed among communities at later stages—for instance, the costs of industrial waste management and savings brought by purchasing and operating cutting-edge technologies may affect different communities based on socioeconomic status or location in environmental justice areas.[9]

Theme 2. Breadth of pre-existing knowledge review

These metrics deal with the diversity of sources consulted to inform research questions, designs, and conclusions, with the goal of engaging broader knowledge sources early in R&D to promote cultural compatibility and easier technology adoption. These metrics codify the value of broadening interactions with traditional academic literature, with an emphasis on reviewing social science[10] and scientific research from diverse authors to combat citation

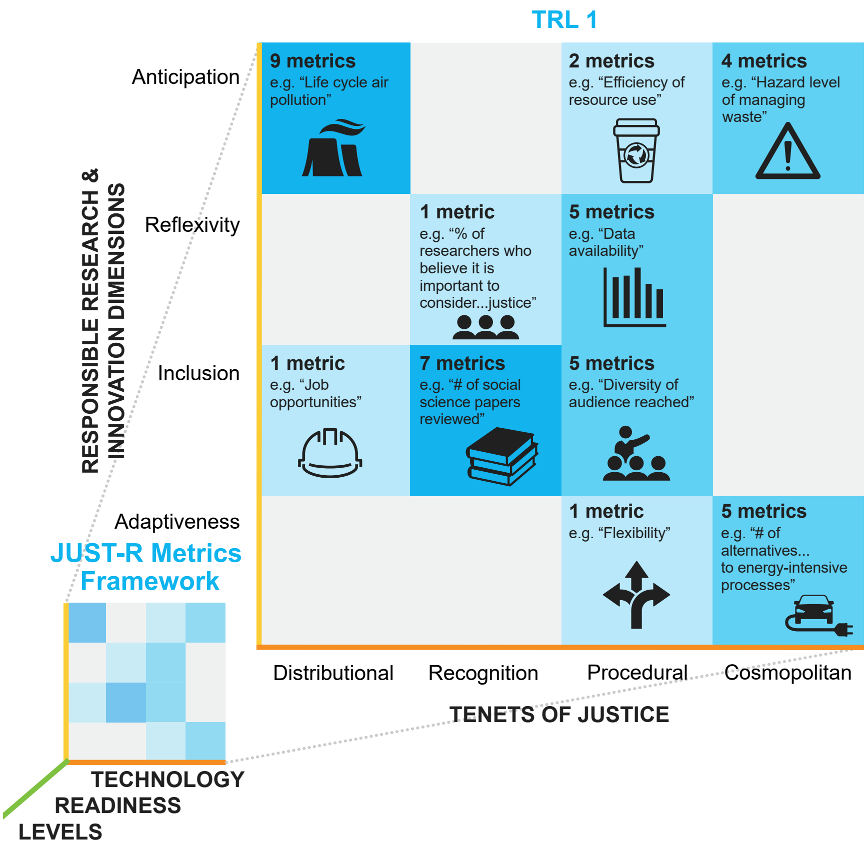

Figure 1. The JUST-R metrics framework

Metrics in the JUST-R framework are organized across RRI dimensions, tenets of energy justice, and TRLs. Distribution of metrics for the earliest stage of R&D (TRL 1) spans all RRI dimensions and all selected tenets of energy justice.

gaps between authors of different identities[11] that reveal missed opportunities to learn from members of disadvantaged communities in attempting to develop technologies that consider their needs. There is also value placed on consulting community-based knowledge, such as journalism, activist work, or indigenous knowledge, to directly incorporate community voices into research designs and directions. Knowledge mobilization[12] is particularly useful early in R&D, when the technological concept is highly general and the specific end user community is not yet known, and lays a foundation for employing community-based participatory research at later stages. Figure 3 describes resources researchers can use as starting points toward meeting these goals.[13,14]

Theme 3. Distribution of research results

These metrics treat knowledge as a valuable output product of research and measure who benefits from it, promoting broad dissemination of results to both scientists and the public to accelerate technology development, aid efforts of community organizations, enable early detection of social concerns, and further facilitate community-engaged research at later stages. As public trust in science increases with familiarity,[15] public understanding of early-stage research is expected to ease technology acceptance, particularly if researchers leverage results dissemination as an opportunity for dialogue. "Nonacademic reports" and "nonacademic oral presentations" are separated to ensure results are presented in appropriate formats to meet the needs of broad audiences, and team diversity is referenced with emphasis on the distribution of benefits among the team to address inequities faced by underrepresented contributors.

Theme 4. Distribution of hazard exposure during the research life cycle

These metrics refer to the distribution of exposure to hazards associated with the research life cycle, going beyond lab workers to consider supply chain workers and community members. As in Theme 1, these metrics span hazards not generally included in lab safety assessments, such as those associated with raw material extraction or wastewater contamination, and assessing phases of the research life cycle individually offers insight into how hazards may be distributed between communities on scaleup. This brings elements of cosmopolitan justice into the framework by creating space to consider, for instance, health impacts of cobalt mining for battery research on local children[2] even if they are not end users of resulting technologies.

Theme 5. Identification of set vs. flexible parameters

Finally, these metrics encourage early exploration of parameter spaces of emerging technologies to elucidate where future research should focus to maximize likelihood that products will be deployable at scale in relevant environments without significant negative impacts. By quantifying alternatives explored to potentially harmful processes or parameters explored to ensure function in diverse geographies, value is placed on thinking creatively and questioning standard practices, rather than succumbing to tradition in the research field. Exploring parameter spaces early encourages efficient R&D by enabling researchers and decision-makers to avoid situations where a negative impact associated with a critical technological component is identified

Energy Justice			
Distributional	**Recognition**	**Procedural**	**Cosmopolitan**
• Life cycle greenhouse gas emissions[5] • Life cycle water consumption[5] • Life cycle air pollution[5] • Land use[5] • Job opportunities[6] • Potentialities of the research to impact positively/ negatively on some social groups[6] • Concentrations of pollutants or toxins[7] • **Hidden process costs:** - **Estimated cost of managing waste generated by the research** - **Estimated cost of energy consumed during the research** - **Projected cost savings from operating the new technology vs. competing technologies**	• Education[6] • Institutional representation[8] • Level of ability of the research problem to address an access problem of a disadvantaged social group[6] • Percentage of researchers who believe it is important to consider/address issues related to social justice/ inclusion in their research methodology[6] • Compatibility with culture[6] • **Breadth of pre-existing knowledge review:** - **Number of social science papers reviewed** - **Diversity of authors of scientific papers reviewed** - **Number of nonacademic sources reviewed**	• Efficiency of resource use[6] • Levels of safety[6] • Transparency[6] • Data availability[6] • Information disclosure[8] • Accountability level[6] • Capability to communicate to stakeholders[6] • Flexibility[6] • **Distribution of research results:** - **Proportion of results published open access** - **Number of nonacademic reports of results** - **Number of nonacademic oral presentations of results** - **Diversity of audience reached** - **Diversity of team members credited for and publicly presenting work**	• **Distribution of hazard exposure during the research life cycle:** - **Hazard level of extracting or synthesizing material inputs** - **Hazard level of laboratory processes** - **Hazard level of managing waste** - **Extent to which hazards would increase at industrial scale** • **Identification of set vs. flexible parameters:** - **Number of alternatives explored to waste-intensive processes** - **Number of alternatives explored to energy-intensive processes** - **Number of alternatives explored to hazardous or unethically sourced materials** - **Number of environmental parameters tested** - **Number of nontechnological solutions explored to solve key problems within the research**

Figure 2. JUST-R metrics applicable to the earliest stage of R&D

Summarized metrics for TRL 1 categorized by the primary tenet of energy justice they aim to apply, with existing metrics from literature.[5–8] New metrics and themes are in bold. Note that certain metrics overlap categories; for instance, "breadth of pre-existing knowledge review" metrics also evoke elements of procedural justice.

only after significant time and funding have been spent. Here, it is paramount to report alternatives explored, even if they do not yield promising results, so future work can build off these ideas and to provide information to decision-makers on whether certain costs, hazards, or other impacts are likely to be mitigated with additional research or if they may be endemic to the technology.

Case study evaluation

As a case study to demonstrate the proposed metrics, we use previous work on structural characterization of colloids in lead halide perovskite precursor inks—relevant to developing next-generation photovoltaics with low cost and facile processing.[16] Despite these applications, the project focuses only on material structure and processing, not device fabrication or testing, thus exemplifying the device-driven but science-focused research common in early-stage energy R&D, where future technologies are a motivation but not the main consideration of the work.

In the case study, we apply the 20 new metrics and consider for each: (1) a general assessment, (2) what could have been done differently, and (3) potential barriers, detailed in Table S6. Ideally, these metrics would be applied at the start of a project to inform research directions (a blank worksheet is included in the supplemental information for researchers interested in assessing new work); however, the post-completion assessment is valuable in demonstrating usability of the metrics and the thought processes they provoke. Overall, 27 unique ideas are generated for what could have been done differently, ranging from leveraging technoeconomic analyses in designing the research to surveying audiences after presentations to understand how communities perceive the work. As shown in Table S7, these ideas could have been implemented throughout the project timeline had the metrics been evaluated at the start of the project. The case study

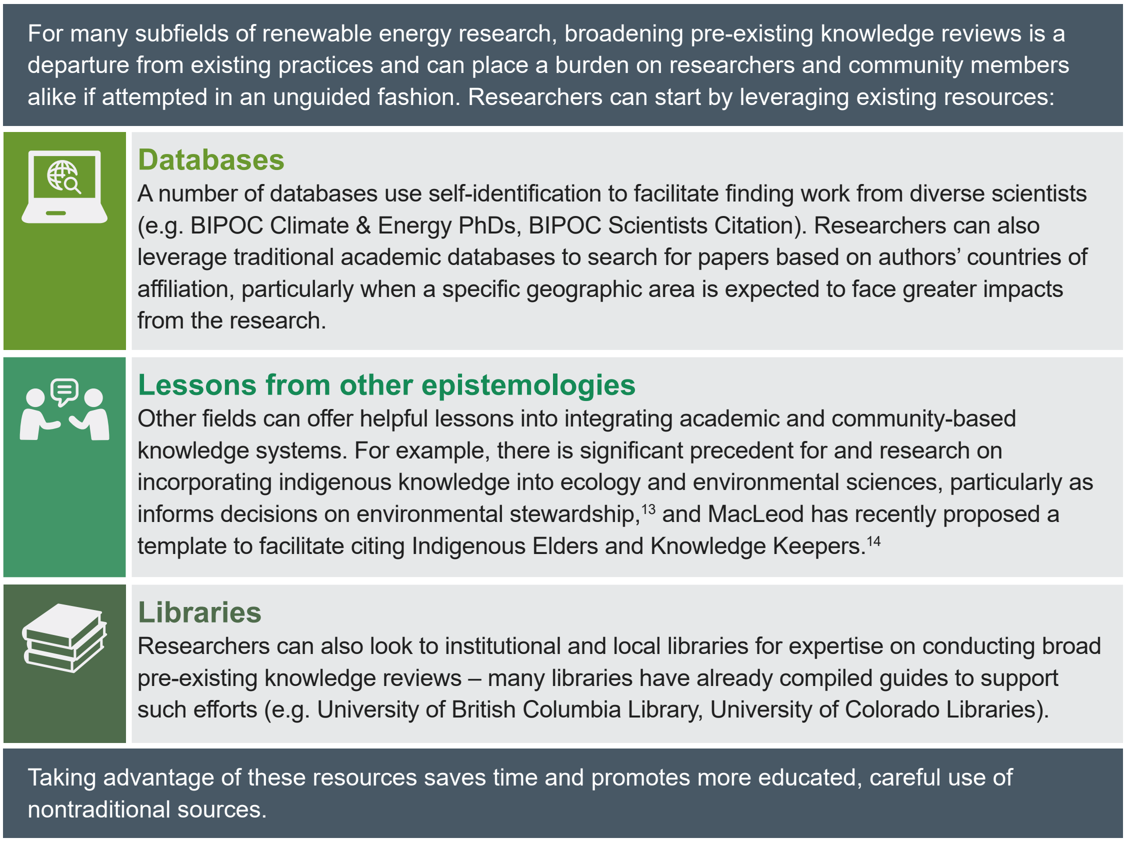

Figure 3. Resources for broadening pre-existing knowledge reviews
Resources to aid in achieving Theme 3 metrics on broadening pre-existing knowledge reviews to include academic and nonacademic knowledge from diverse sources.[13,14]

also highlights typical barriers to taking such actions and overall reveals five key lessons:

1. **Tradeoffs between energy justice metrics and technical metrics.** Tradeoffs are reflected in the six metrics in Table S6 that would improve with use of a lead-free perovskite, even though these have yielded less efficient solar cells.[17]
2. **Potential for tokenism.** This comes across particularly in "distribution of research results" metrics, where the quality of presentations, level to which they were adapted to the audience, and extent of audience engagement are obscured by the more easily quantified number of presentations.
3. **Subfield variability.** Certain metrics prompt more thinking than others depending on the subfield. For instance, "number of alternatives explored to energy-intensive processes" is not as challenging to consider as "number of alternatives explored to hazardous or unethically sourced materials," since perovskites are of interest partly due to their already low-cost, low-energy fabrication.
4. **Implicit comparisons.** Evaluation of many metrics is easier with a benchmark in mind. This is evidenced by use of "relatively high/low" in assessments in Table S6, where comparisons are implicitly drawn to research practices or technologies perceived as standard, though a fully quantitative approach could also be employed.
5. **Reflection of scientific cultural values.** "Time burden" arises as a barrier for many metrics, but the difference between a burden and a worthwhile use of time depends on one's values. In the case study, this subjectivity particularly disfavors "breadth of pre-existing knowledge review" metrics.

Discussion

These lessons shed light on hurdles that may arise when applying the JUST-R framework to assess or manage future research, particularly when it comes to decisionmaker values. Whether metrics are used institutionally to assess current or proposed projects or by project teams to manage energy justice implications of ongoing work, the researcher's and institution's values are highly intertwined. For instance, a researcher's choice to study less hazardous chemistries at the expense of poorer performance can have multifaceted justice implications (e.g., on technology accessiblity and cost or on environmental health in disadvantaged communities). How these choices are weighed hinges both on personal values and values demonstrated when research institutions and the scientific community allocate rewards like promotions, funding, or citations. While constraints brought by energy justice considerations can lead to creative new ideas,[18] we must acknowledge that for early-stage research, equitable deployment and use of technologies is a long-term reward, often decades away, compared to short-term rewards provided by institutions. Thus, attention must be paid to values promoted by the research community. Key questions to consider are: to what extent do we value energy justice, technical, economic, or other metrics of research success? Do our reward systems encourage making choices in line with those values?

A critical next step toward enhancing the effectiveness of this framework is to tackle the challenge of subfield variability. Energy technologies are diverse, and early-stage energy research spans multiple disciplines. As in the case study, we expect researchers will find that certain metrics carry different meanings in their work, depending on the context of their field. Moreover, while we hope Tables S1–S4 will aid researchers by introducing them to metrics applicable to their research stage, the TRL designations should be viewed flexibly. Certain projects may be able to transition from early- to late-stage metrics at different points in technology readiness than we have laid out and should do so, ideally discussing these considerations in publications to inform future work. Perhaps most pressingly, researchers can engage in the same process conducted in this work to refine or develop further metrics specific to their research and communities—it is expected and desired that this be a dynamic framework as new technologies and social concerns arise.

Conclusion

Current early-stage energy research will determine the design and impacts of technologies needed for a clean energy future. Here we have proposed the JUST-R metrics framework to facilitate measuring and managing energy justice considerations starting from the earliest stages of R&D. The novelty of this framework lies in its deliberate focus on metrics immediately applicable to early-stage research, demonstrated through a case study assessment and discussion of key lessons learned. With a combination of clearly defined institutional values and individual researcher efforts to further expand the framework, JUST-R provides a foundation to embed energy justice considerations into early-stage R&D to promote development of more just and effective technologies necessary for a sustainable clean energy transition.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.01.007.

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AUTHOR CONTRIBUTIONS

Conceptualization, K.A.; methodology, N.S.D., E.G., B.K.A., M.H., and K.F.; investigation, N.S.D. and E.G.; writing – original draft, N.S.D. and E.G.; writing – review & editing, N.S.D., E.G., B.K.A., M.H., K.F., and K.A.; project administration, K.A.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

One or more of the authors of this paper self-identifies as an underrepresented ethnic minority in their field of research or within their geographical location. One or more of the authors of this paper self-identifies as a gender minority in their field of research. One or more of the authors of this paper self-identifies as a member of the LGBTQIA+ community. One or more of the authors of this paper self-identifies as living with a disability. One or more of the authors of this paper received support from a program designed to increase minority representation in their field of research. While citing references scientifically relevant for this work, we also actively worked to promote gender balance in our reference list.

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