Title

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Quantitative approaches to energy justice: The theory and praxis of examining fair access to reliable electricity

by

Isa Ferrall

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Energy and Resources

and the Designated Emphasis

in

Development Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Daniel M. Kammen, Chair
Associate Professor Duncan Callaway
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Abstract

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Energy justice has emerged as a rapidly growing academic discipline at the intersection of social justice, energy policy, technologies, and the environment. It considers how both the benefits and burdens of our energy system are distributed across society, particularly as our system transitions to address climate change. This dissertation contributes to this emerging field by investigating issues of electricity access, distribution of energy burdens, and fairness of energy decision-making. By combining technical knowledge of electric power systems, methods from applied data science, and theory from energy justice, the following research examines the implications of inequitable access to reliable electricity around the world. Part I of this dissertation summarizes and reviews the landscape, theory, and methods of energy justice in order to motivate Part II which applies these methods and concepts to three timely energy justice issues.

In brief:

- Ch 1: Introduction and Motivation - Offers an overview of the landscape and evolution of the energy justice field through a systematic review and analysis.
- Ch 2: Theory - Investigates the philosophical roots of energy justice theory by incorporating broader debates and approaches from political philosophy and other social justice disciplines.
- Ch 3: Methods - Reviews methods for measuring distributive energy justice via equality

and equity, noting their strengths, weaknesses, and opportunities to inform decision-making.

- Ch 4: Application 1: Solar and gender - Using mixed-methods, this chapter investigates how the distributional benefits of off-grid solar are mediated by gender and class in rural Tanzania thereby investigating inequities in access to the benefit of solar electrification.
- Ch 5: Application 2: Reliability of energy access - This chapter empirically studies the reliability of household electricity access in Tanzania, Kenya, and India using data from a diverse set of technologies. It thereby investigates inequities in how the burden of unreliability changes across different energy access solutions.
- Ch 6: Application 3: Rotating outages - This final application chapter quantifies the extent to which a uniquely shareable energy burden of rotating power outages was inequitably distributed across communities in California in August 2020 and investigates the procedures that led to such outcomes.
- Ch 7: Conclusion

“let there be [reliable] light [for all]” ∼ adapted UC Berkeley motto

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Part I

Theory

Chapter 1

Introduction

1.1 Overview of Energy Justice

> "Energy justice refers to 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].

As both a goal and an emerging academic field, energy justice is incredibly multifaceted. The literature on energy justice evaluates the justice implications of a wide range of technologies (solar, wind, fossil fuels, buildings, transportation, grids, etc.) on many different levels of demographic and social vulnerability (minorities, gender, income, health, etc.). In addition, energy justice questions encompass:

- Geographies all around the world,
- Upstream and downstream effects - from the mining of rare earth minerals to waste cycles,
- The time scale of impacts,
- Whether injustices occur in the access-to or realization-of the energy technology or quality,
- Whether energy benefits or burdens are being distributed,
- in addition to many others.

Within this diverse energy justice landscape, the application chapters of this dissertation focus on equitable access to solar and reliability electricity across gender (in Ch 4), energy systems (in Ch 5), and other markers of vulnerability such as minority status and health (in Ch 6). While Ch 4 and 5 are located in East Africa, Ch 6 applies similar equity lenses to questions of electricity outages in California. All three applications of energy justice principles study present-day impacts, however they differ in terms of whether energy benefits (of access to solar in Ch 4) or burdens (of unreliable electricity in Ch 5 & 6) are distributed.

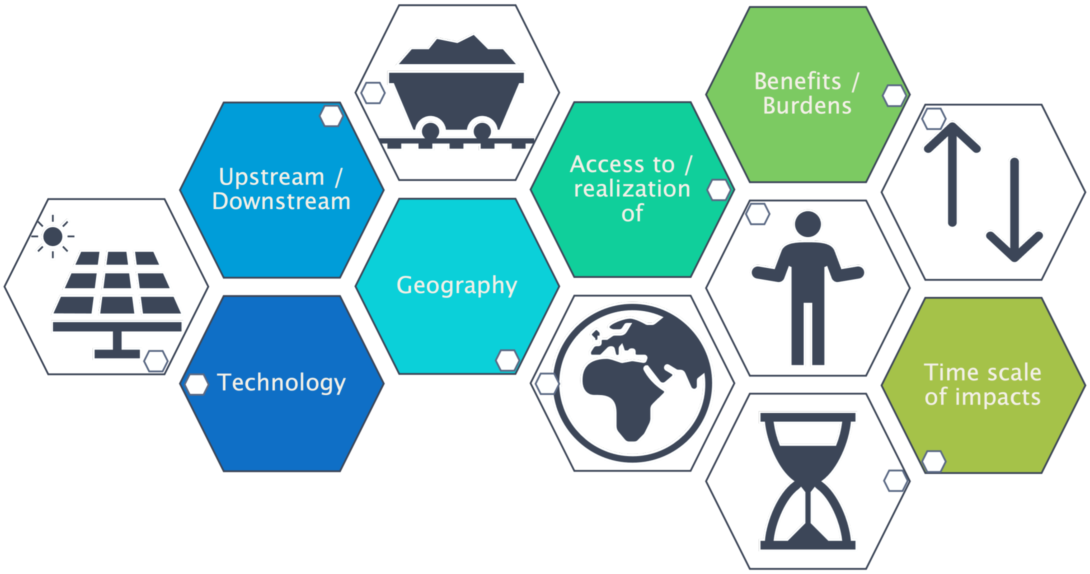

Figure 1.1: Multiple interlocking facets of energy justice

Not only is the field multifaceted, there is also a plurality of theories. In a 2016 conceptual review of the field, Jenkins et al. proposed distributive, procedural and recognition justice as three core tenets [2]. Distributional energy justice evaluates the allocation of the benefits and burdens of energy. Procedural energy justice is the equitable engagement of all stakeholders in decision making, and requires "participation, impartiality and full information disclosure." And finally, recognition energy justice calls for fair representation and the offering of complete and equal political rights to all individuals [3]. These three tenets, which are placed in the middle tier of Figure 1.2's theory pyramid, are often accompanied by restorative justice which is placed at the top of the pyramid in acknowledgement of prior harms to low-income communities and communities of color and therefore, the unequal baselines and endowments.

In addition to the three tenets, Sovacool et al. often promotes an approach consisting of many core principles that has included: human rights concerns, availability, affordability, due process, good governance, transparency and accountability, sustainability, intra- and inter-generational equity, responsibility, resistance, and intersectionality [4–6].

This dissertation is primarily informed by theories of distributive energy justice (the unequal distribution of modern energy services and burdens across society) and procedural energy justice (due process, representative justice, and justice as public participation). Distributive justice is often characterized by three aspects: what goods are distributed, between what entities, and what is the proper mode of distribution whether based on need, merit, or other factors. Procedural justice centers around who gets to decide and set rules and laws, which parties are recognized, by what processes, and how impartial are those involved [5].

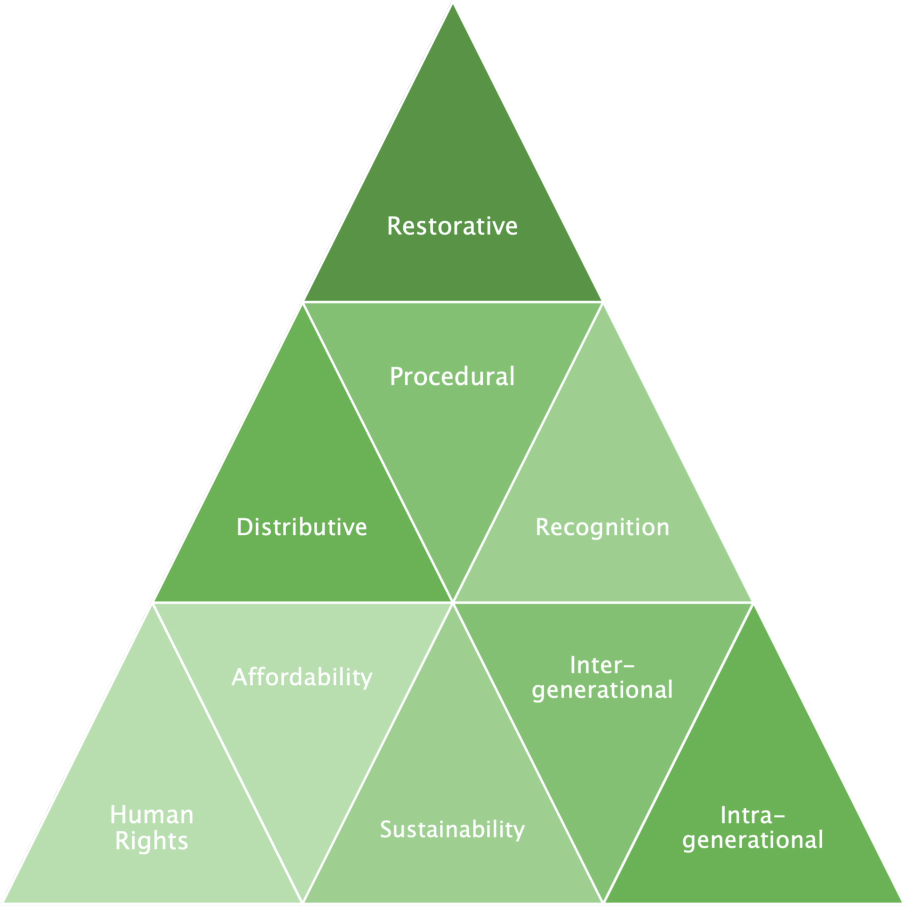

Figure 1.2: Plurality of theories of energy justice

Finally, the field has a long dictionary of overlapping terminologies. The Initiative for Energy Justice's Workbook discusses the range of terms associated with 'energy justice' broadly, and how these terms are used by both academics and practitioners [1]. Common terms include energy justice, energy equity, energy democracy, energy insecurity, energy burden, and energy poverty which each have different associations. Baker notes that in general, practitioners and advocates make explicit references to centering the voices of low-income communities and communities of color, while academics tend to take a more measured approach by not explicitly centering the voices of the studied communities. Table 1.1 reproduces several tables from Baker's workbook in order to define each of the major terms and note the frequency of usage across different disciplines.

This dissertation predominantly uses the term 'energy justice' as it is one of academia's most commonly used terms and is also widely understood. 'Energy access' is also frequently

Term	**Definition**	**Usage across practice and research**		
		Social Science & Academia	**Practitioners**	**Law**
Energy Justice	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 by the energy system.	Common	Infrequent	Infrequent
Energy Equity	Same as Energy Justice	Rare	Common	Infrequent
Energy Democracy	The notion that communities should have a say and agency in shaping and participating in their energy future.	Common	Common	Common
Energy Insecurity	The inability to meet basic household energy needs due to the high cost of energy.	Infrequent	Infrequent	Common
Energy Burden	Amount of overall household income spent to cover energy costs.	Common	Common	Infrequent
Energy Poverty	A lack of access to basic, life-sustaining energy.	Rare	Infrequent	Infrequent

Table 1.1: Energy Justice Terms and Usage. Reproduced from Initiative for Energy Justice Workbook [1]

used in this dissertation as defined by the United Nations' Sustainable Development Goal #7 to "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [7]. Energy access is therefore most closely aligned with energy poverty and is inherently an issue of energy justice as described in Chapter 4 of this dissertation in the section titled 'Energy justice through energy access'. While this dissertation does not actively investigate 'energy insecurity' as defined in Table 1.1, findings on 'economic outages' or shut-offs due to bill non-payment demonstrate its rising importance as found in Chapter 5 in the section titled 'Policy implications for addressing energy poverty in the Global South'.

1.2 Comprehensive and systematic bibliometric review of energy justice

Literature on environmental and climate justice as well as discussions of inequality and justice from political philosophy and ethics compose energy justice's core intellectual roots [1]. While energy justice builds on these longer established disciplines, the field itself is quite new, only emerging since 2017. The multiple facets, plurality of theories, and large dictionary of terms offer the field the opportunity for wide reach and transcendence of many issues, but also demonstrate its scattered nature. In the most comprehensive review to date, Jenkins et al. notes that "efforts are generally more multidisciplinary than interdisciplinary, and it is a potentially 'corruptible concept', highly vulnerable to a range of political agendas" [8]. In order to systematically and comprehensively review this complex literature, this chapter makes a unique contribution by applying bibliometric methods to review published energy justice research.

Bibliometrics is the use of statistical methods to review and map scientific literature through systematic, transparent, and reproducible processes. Bibliometrics is a particularly suitable scientific mapping technique for voluminous, fragmented, and controversial research fields by providing objective and reliable analyses It can provide structured analysis to a large body of information, infer trends over time and themes researched, identify shifts in the boundaries of the disciplines, detect the most prolific scholars and institutions, and present the "big picture" of a field of research [9].

This chapter performs a bibliometric review of academic energy justice publications primarily using the R-package 'Biblometrix' described by Aria and Cuccurullo [9]. Their flexible, open-source tool allows scholars to follow the complete scientific mapping workflow using substantial and effective statistical algorithms and data visualization tools.

While Jenkins's review was systematic and comprehensive of their stated scope, by using time-intensive manual methods, they were only able to review 155 academic papers published between 2008 to 2019 [8]. The computational methods used in this analysis allow for the expansion of the time span, search terms, and types of publications to review 2,290 academic publications published on or before January 31st, 2022. Table 1.2 compares the scope and search criteria of this review to that of Jenkins et al..

The primary difference is the dramatic expansion of the review's search terms in this analysis. Instead of narrowing the search to only papers that include "energy justice" explicitly in the title, abstract or keywords, the search is broadened to include all of the terms that Table 1.1 identifies from the social science and legal literature [1]. All terms listed in Table 1.1 were searched, as well as corollaries to each of the terms, and their plural forms. By using an asterisk wildcard character as a simplified form of regular expressions, the search term "energy *justice*" can search for documents that include energy justice, energy injustice, energy justices, or energy injustices. This analysis does not explicitly include the corollary "energy security" as this refers to a different well-established literature at the intersection of electric power systems, risk, and global energy governance. Still, several papers on energy

Characteristics	**Jenkins et al. (2021) [8]**	**This review**
Search terms	'energy justice' in the title, abstract, and keywords	'energy *justice*', 'energy *equit*', 'energy democracy', 'energy insecurity', 'energy burden*' or 'energy poverty' in the title, abstract, author keywords, or keywords plus
Time span	1 January 2008 - 31 December 2019	before 31 January 2022
Databases	Science direct, Project muse, Hein online, SpringerLink, Taylor and Francis Online, Wiley online, Sage journals, Annual reviews	Clarivate Analytics Web of Science (WoS) Core Collection
Document types	Full-length articles and review papers that were peer-reviewed and published in English	Full-length articles, review papers, proceedings papers, books, and book chapters
Total publications	155	2,290

Table 1.2: Scope and search criteria of existing systematic energy justice reviews

insecurity as the corollary to energy security rather than the definition in Table 1.1 have been identified in the search results. Since ‘energy justice’ broadly-speaking is such a fragmented and multidisciplinary field, a narrow selection of search terms risks missing large portions of the literature.

The starting date of this search is not limited in order to capture the full history of this field. This allows us to include publications such as a Harvard Environmental Law Review article from 1983 titled “Energy Equity for the Poor: The Search for Fairness in Federal Energy Assistance Policy” by Kenneth A. Manaster. Long ahead of their time, Manaster discusses the financial burden of high energy costs placed on Americans since the 1973 OPEC oil embargo [10]. The earliest article found was published in 1983; there were only 14 results published before 2000, and only 48 results between 2000 and 2007. Therefore, the inclusion of the early results that were not included by Jenkins et al. does not significantly change the following analyses. Nonetheless, they are included for comprehensiveness.

This analysis searched the Clarivate Analytics Web of Science (WoS) Core Collection database for depth, standardization of documentation, and integration with the bibliometrix R-package. The WoS Core Collection is one of the largest multidisciplinary academic databases and the world’s original citation index for scientific and scholarly research. Their curated collection contains the contents of over 21,100 unique peer-reviewed scholarly journals covering over 250 disciplines. 40% of the energy justice literature is published in 9 journals: Energy Research and Social Science (n=252), Energy Policy (n=215), Sustainability (n=84), Energies (n=76), Energy Economics (n=68), Renewable and Sustainable Energy Reviews (n=68), Energy and Buildings (n=63), Applied Energy (n=47), and Energy for Sustainable Development (n=43). Source clustering through Bradford's law identifies the first 6 of these as core sources, or the nucleus of journals particularly devoted to this subject. Since this database has complete coverage of these most popular journals, the use of this single database is more than sufficient for the following analysis. As a verification step, the search terms from Jenkins et al. (2021) were reproduced in the WoS Core Collection resulting in 187 academic articles, which is larger than, and broadly inclusive of, their 155 article review. This may be due to later steps by the authors to remove not articles they found not to be relevant to the overall review even though the articles fit the explicit search criteria. As found in this review, the articles that fit the name of the search criteria but not its spirit may have focused on energy security as in national security risk, energy burden as in metabolic energy use, or may be published in a language other than English.

Finally, the acceptable document types were expanded to include articles, reviews, proceedings papers, books, and book chapters. Book reviews, corrections, notes, letters, and editorial materials were all excluded as they were largely repetitive of the original content provided in the included document types. This review also did not limit the language of publication. Not limiting publications to just those published in English added 46 results published between 1997 and 2021. Many of these articles defined 'energy poverty' for different local contexts such as in Italy, Mexico, or Argentina and all metadata (most importantly the title, abstract, keywords) were written in English. By including these diverse global perspectives, this review prioritizes equity in its process as well as its subject matter.

This analysis has three key limitations. First, this analysis does not currently use the full text of articles, only the metadata which includes the title, abstract, authors, journal, research area, publication date, keywords, citations, times cited, funding information, among others. While the full text of many of the included articles are open access, many others remain behind journal paywalls. The crucial contribution of this bibliometric review to the field lies in its reproducibility and breadth. Therefore this analysis does not pursue the large additional methodological and computational burden that compiling and digitizing the full texts entails.

Second, the broad search terms result in the inclusion of several publications that are not about energy justice as defined here. For example, the term "energy burden" is used in biology, microbiology, zoology, and ecology to refer to metabolic energy burden whether on an organism scale or societal systems scale. Only 15 of the 2,290 publications fit the above search terms and "metabol* in the title, abstract or keywords. Their limited presence is acknowledged but not removed at present from the much larger analysis. En masse, the strength the systematic methods outweighs the limited presence of outliers.

Finally, using a scientific publication database excludes the important energy justice grass-roots and activist perspectives. Compiling and extending similar methods to this extensive grey literature is a promising opportunity for future research. Fuller and McCauley's

2016 article titled ‘Framing energy justice: perspectives from activism and advocacy’ provides an excellent starting point by developing an analytical framework for assessing the emergence of energy justice in the activist and advocacy areas through a survey of organizations in Philadelphia, Paris, and Berlin [11]. The Energy Justice Workbook expanded upon Fuller and McCauley’s work in Section 1.1 on Energy Justice in Practice [1]. In this section, the authors reviewed statements of practitioners and advocates finding that they rely less on the terms “energy justice” and more on “energy equity” or “energy democracy”. Carley et al. (2021) provides a non-comprehensive review of energy justice programs in the United States on which future work can be built [12]. However, these cross-cutting energy justice issues are faced by communities around the world, therefore a focus on any one country may leave out key themes.

Characteristics	**Value**
Time span	1983:2022
Sources (Journals, Books, etc.)	744
Documents	2290
Average years from publication	4.37
Average document citations	17.13
Average annual document citations	2.98
Number of unique references	91,322
Document Types	1739 Articles; 83 Article/book chapters; 38 Article/early access; 23 Article/proceedings papers; 7 Books; 15 Editorial material/book chapter; 203 Proceedings papers; 176 Reviews; 3 Review/book chapters; 3 Review/early access
Keywords	2972 Keywords Plus; 5221 Author’s Keywords
Authors	5107 Authors; 6873 Author Appearances; 357 Authors of single-authored documents; 4750 Authors of multi-authored documents
Collaboration	447 Single-authored documents; 0.448 Documents per Author; 2.23 Authors per Document; 3 Co-Authors per Documents; 2.58 Collaboration Index

Table 1.3: Descriptive summary of this review’s contents

The energy justice field has grown quickly since 2009, with a compound annual growth rate of 12.15%. Jumps in productivity in 2017 and 2020 seen in Figure 1.3 can be associated with turning points in the field. As of the 31st of January 2022 there were already 35 papers published, further indicating that the field has a strong growth trajectory.

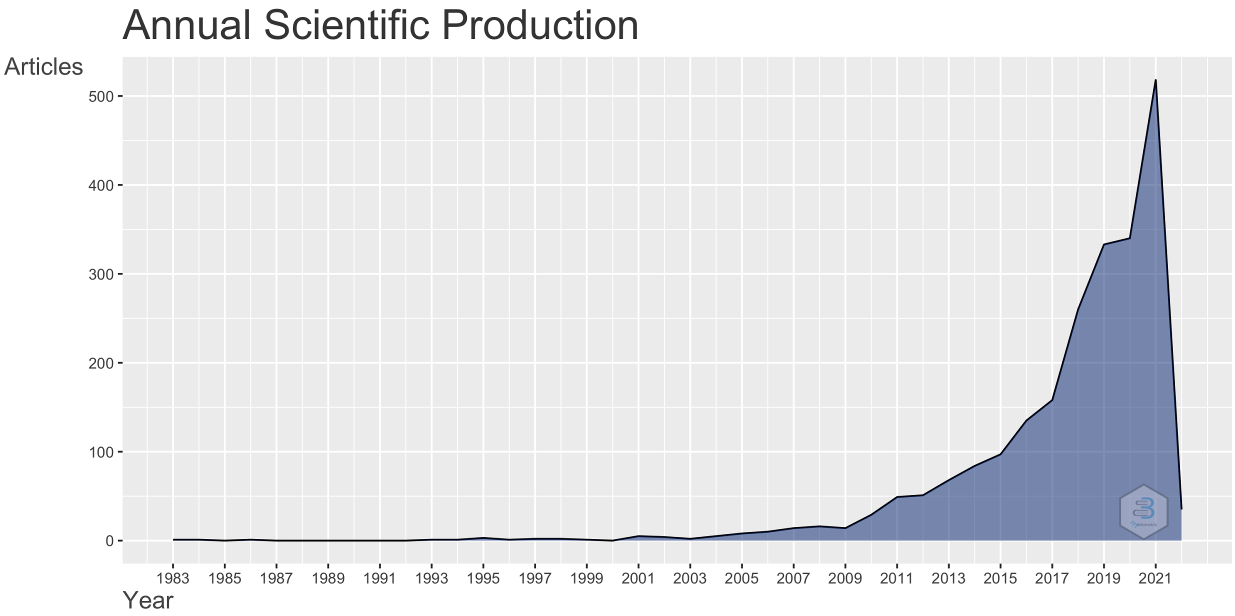

Figure 1.3: Annual Scientific Production Jan 2000 - Jan 2022

As shown dramatically in Figure 1.4, Benjamin K. Sovacool is by far the most prolific author in this field with 66 publications. Even when considering fractional co-authorship, Sovacool has a fractionalized authorship (i.e. 2 co-authors each are attributed 0.5 fractionalized authorships) of 32.2; three times higher than the next most prolific author. The domination of this academic literature by one author indicates both their core contribution to the growing field, but also the fields immaturity as an academic dialogue. One might expect the publications in this ethical topic to have a stronger and more diverse authorship. While energy justice is rapidly growing field that has gained much academic interest, it may not yet have matured into a thriving intellectual exchange among many researchers. Notable other authors ranked by their number of publications include Bouzarovski, McCauley, Urpelainen, Heffron, Hernandez, Reames, Bazilian, and Jenkins.

To distinguish impact within the energy justice field from larger academic import, this chapter separates global and local citations. Global citations measure citations from documents in the entire WoS database reflecting the more common interpretation of a publication's citation count. Local citations measure citations a document has received from within the analyzed collection. Therefore, while global citations reveal publications of interest to the entire academic community, local citations note importance to the field. The list of local citations also includes articles that are not in the original collection but are highly cited by it, further overcoming issues surrounding the inclusion of specific keywords. Figure **??** shows

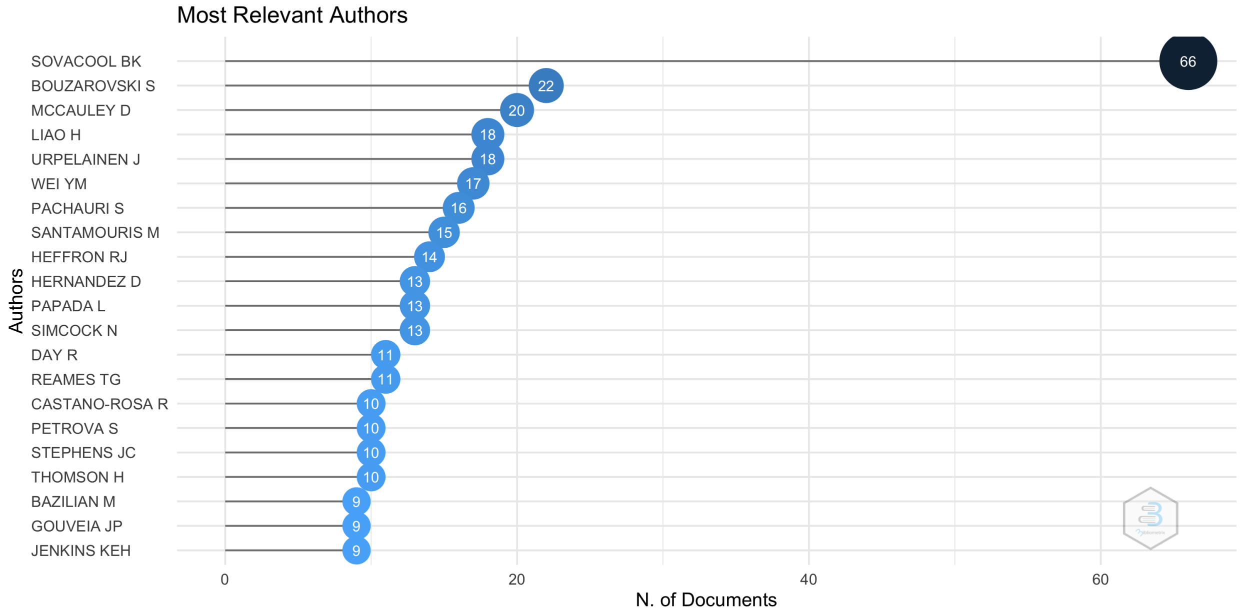

Figure 1.4: Most relevant authors by the number of documents published

the 10 most cited documents globally (top) and locally (bottom).

The example of the most globally cited article immediately demonstrates the importance of evaluating local citations instead of global citations in a bibliometric review process. Jacobson and Delucchi's 2011 controversial article titled "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials" has the most global citations at 811 [13], but no local citations. Therefore, within this field, it has little relevance, even though it has the most overall citations. Upon further inspection, this article was included in this review because of its use of the term "energy insecurity" in the first sentence of the abstract. The usage of 'Energy insecurity' as the corollary to 'energy security' and in only the motivating sentence both serve to indicate its reduced focus on energy justice.

Jenkins's 2016 review titled "Energy justice: A conceptual review" is the most locally cited article and the second most globally cited article [2]. Therefore, it has both significant import to the larger academic community, as well within the energy justice community. This review introduces the three tenets approach of distributional, recognition, and procedural justice and proposes a research agenda for the field. Chapter 2 of this dissertation further investigates the theoretical underpinnings of this specific review.

Similar to identifying the most locally cited articles, one can identify the most locally cited authors. While Sovacool co-authored the most number of documents in this review (n=66) followed by Bouzarovski (n=22) and McCauley (n=20), the order between these top three authors changes when examining locally cited co-authorships. Bouzarovski has the

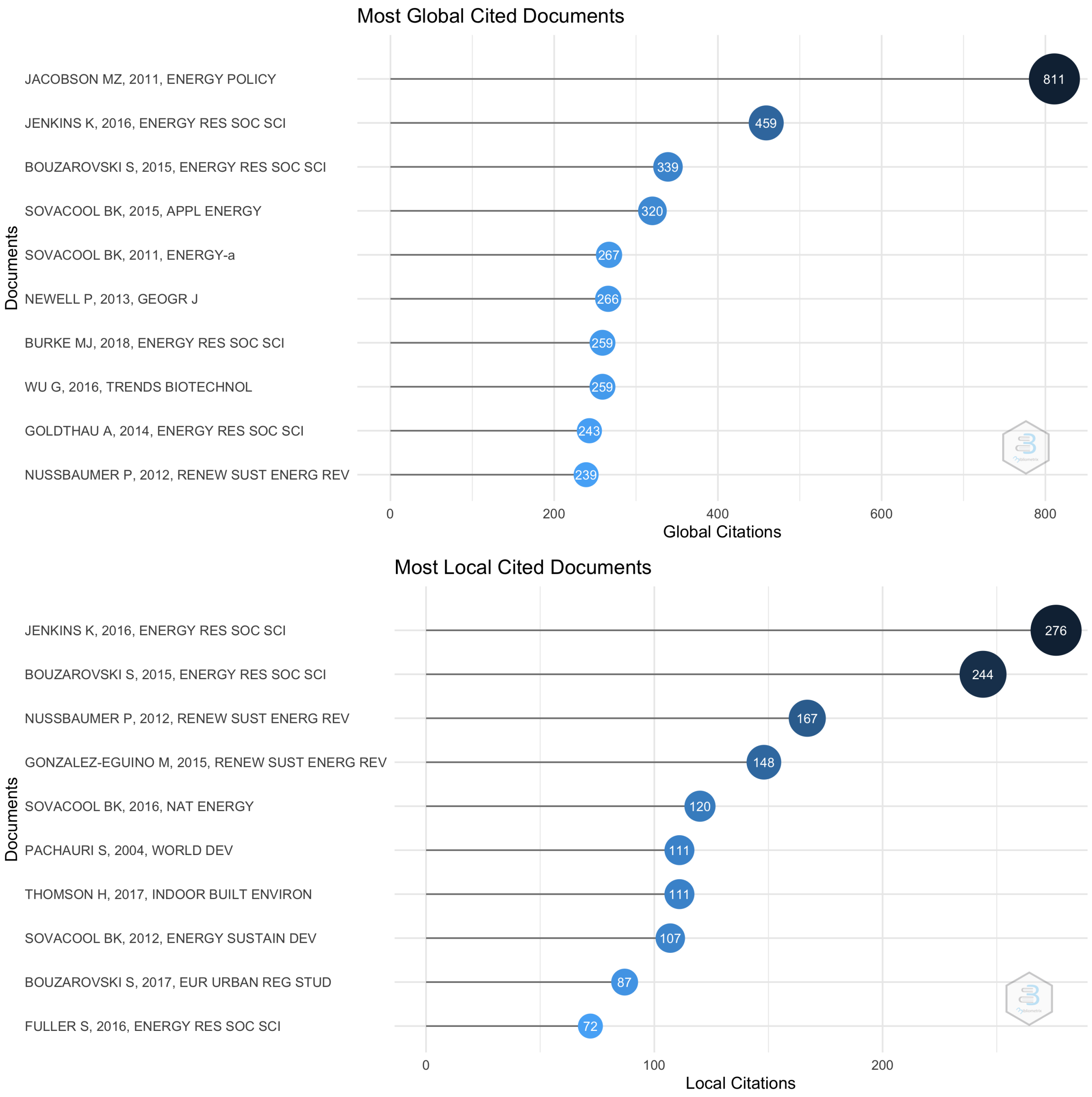

Figure 1.5: Most cited documents, globally (top) and locally (bottom)

most local citations at 559, followed by Sovacool at 461, and McCauley with 425. These findings indicate that while Sovacool may be co-authoring the most publications in this energy justice review by a large margin, publications within the review are 3-4 times as likely to cite work co-authored by Bouzarovski or McCauley.

Next, the source of publications is compared between documents in the review and documents cited by publications in the review. Documents in this review were mostly likely to be published in Energy Research and Social Science (11%), but cited documents were most likely to be published in Energy Policy (10.7%). Both of these journals published prescient special issues on energy justice that encourage the academic development of the field. Energy Policy published the special issue 'Exploring the Energy Justice Nexus' in 2017 [14], Energy Research and Social Science published 'Energy demand for mobility and domestic life: new insights from energy justice' in 2016 [15], and Applied Energy published 'Low Carbon Energy Systems and Energy Justice' in 2019 [16].

Overall, there are significant differences between the most globally cited documents and the most locally cited documents indicating the strong inter-linkages between energy justice and related fields. The table below provides brief synopses of the ten most locally cited documents in this review as a way to summarize for readers the key texts recognized within in this diverse interdisciplinary field.

- Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: A conceptual review. Energy Research & Social Science [2]
  - Provides a conceptual review of energy justice and proposes a research agenda
  - Introduces three core tenets theory approach: distributional, recognition, and procedural justice
  - Global context of energy production and consumption
- Bouzarovski, S., Petrova, S., 2015. A global perspective on domestic energy deprivation: Overcoming the energy poverty–fuel poverty binary. Energy Research & Social Science [17]
  - Integrated conceptual framework for research and amelioration of energy deprivation/poverty
  - Context: inability of households to meet their energy needs in developed and developing countries
- Nussbaumer, P., Bazilian, M., Modi, V., 2012. Measuring energy poverty: Focusing on what matters. Renewable and Sustainable Energy Reviews [18]
  - Reviews methods for measuring energy poverty and proposes a new composite index (Multidimensional Energy Poverty Index (MEPI)
  - Context: households in several African countries
- González-Eguino, M., 2015. Energy poverty: An overview. Renewable and Sustainable Energy Reviews [19]

  - Reviews energy poverty defined by the lack of energy access, its measurement techniques, and implications
  - Context: lack of electricity access and use of wood-burning stoves in the developing world

- Sovacool, B.K., Heffron, R.J., McCauley, D., Goldthau, A., 2016. Energy decisions reframed as justice and ethical concerns. Nature Energy [5]

  - Investigates how concepts from justice and ethics can inform energy decision-making on five energy problems - nuclear waste, involuntary resettlement, energy pollution, energy poverty, and climate change
  - Proposes 8-principles theory approach: availability, affordability, due process, transparency and accountability, sustainability, inter- and intra-generational equity, and responsibility
  - Global energy policy context

- Pachauri, S., Mueller, A., Kemmler, A., Spreng, D., 2004. On Measuring Energy Poverty in Indian Households. World Development [20]

  - Proposes a two-dimensional measure of energy poverty combining element of access to different energy types and the quantity of energy consumed
  - Applies measure to a timeseries of energy poverty data in Indian households

- Thomson, H., Bouzarovski, S., Snell, C., 2017. Rethinking the measurement of energy poverty in Europe: A critical analysis of indicators and data. Indoor and Built Environment [21]

  - Critically assess the available statistical options for monitoring household energy poverty in the European Union
  - Lens of vulnerability thinking

- Sovacool, B.K., 2012. The political economy of energy poverty: A review of key challenges. Energy for Sustainable Development [22]

  - Reviews energy poverty and energy ladders with respect to electrification and dependence on biomass fuels for cooking
  - Notes health, gender empowerment, and environmental implications
  - Context: lack of electricity access and use of biomass for cooking in the developing world

- Bouzarovski, S., Tirado Herrero, S., 2017. The energy divide: Integrating energy transitions, regional inequalities and poverty trends in the European Union. European Urban and Regional Studies [23]

  - Analysis of spatial and temporal trends in national-scale patterns of energy poverty in the European Union

  - Lens of development theories of core and periphery and path-dependency
  - Context: energy transitions affecting household energy poverty in the European Union

- Fuller, S., McCauley, D., 2016. Framing energy justice: perspectives from activism and advocacy. Energy Research & Social Science [11]
  - Articulates an energy justice frame from the perspective of advocates and activists in Philadelphia, Paris, and Berlin.

Summarizing these ten most locally cited articles as a whole provides an indicative map of the field overall. For example, four of the articles take a global perspective of their energy justice issue [2, 5, 11, 17], four focus on developing countries [18–20, 22], and the final two examine issues across the European Union [21, 23]. Energy justice is not only global issue, it is also approached by global authors. Figure 1.6 visualizes this diversity of author affiliation locations around the world. An authors' affiliation country does not necessarily represent the article's study location, but it may be indicative.

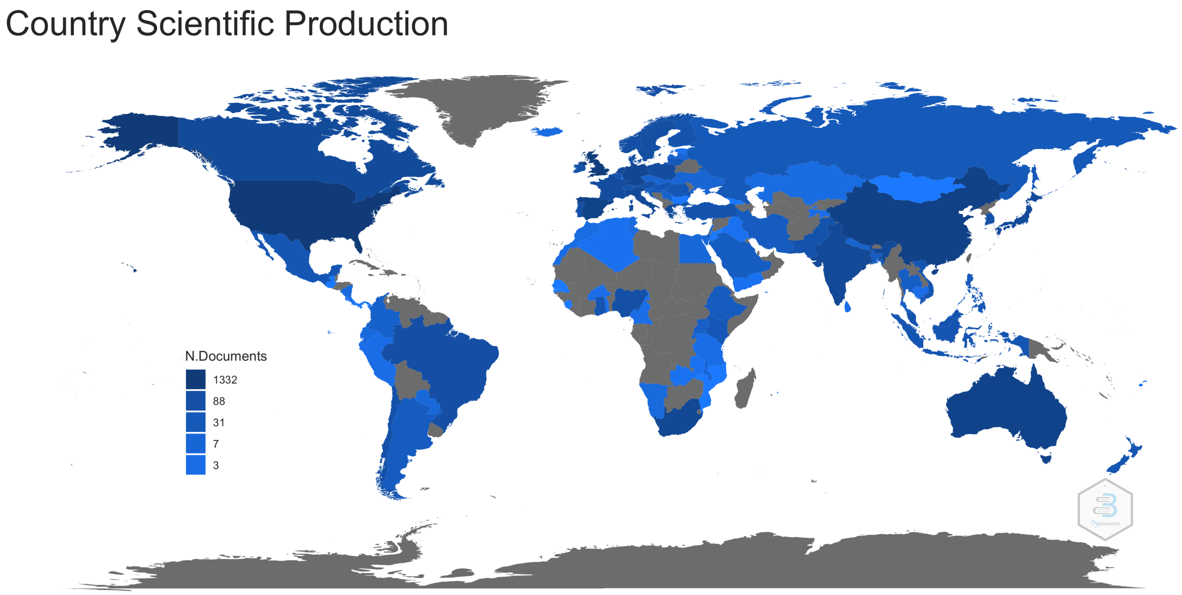

Figure 1.6: Country Scientific Production - number of documents with at least one co-author's affiliation located in each country.

Two of the top ten most locally cited articles present the two dominant theory frameworks: Jenkins et al., (2016) and Sovacool et al., (2016). Detailed further in Chapter 2 of this dissertation, both have made strong impacts on the field even though they have limited engagement with underlying social justice and political philosophy theories of justice. Seven of the ten articles focus on 'energy poverty' as defined by the inability of households to meet their basic energy needs [17–23]. Four of these focus on different measurement techniques [18–21], demonstrating the importance of quantification to energy poverty scholars. Only one of these articles address efforts and perspectives of advocates and activists that have been working on these issues for decades longer than academia [11].

Figure 1.7's representation of author keyword frequency across all 2,290 publications confirms the dominance of the 'energy poverty' branch of energy justice. Authors explicitly included 'energy justice' in only 11% of publication keywords, while 'energy poverty' was found in 26% of publication keywords. Not only are energy poverty and energy access clear energy (in)justice issues, they compose the majority of articles in the field. Prior reviews that do not take into account the varied terminology of this field miss these large contributions.

Of the six search terms (energy justice/equity/democracy/insecurity/burden/poverty) only four appear in the top 50 keywords. Energy poverty ranks first, energy justice ranks second, energy democracy ranks tenth, and energy insecurity ranks twenty-fourth. It is noted that energy access (a subset of energy poverty) ranks seventh, energy security (not the corollary of household energy insecurity) ranks sixteenth, and equity (not associated with energy) ranks fortieth.

Because this review largely draws on academic social science and law literature, one would expect similar findings to The Energy Justice Workbook in terms of terminology usage. While the frequency rankings of energy justice, energy equity, energy democracy, and energy insecurity are largely in line with their findings, this chapter finds significant differences with the usage of energy burden and energy poverty. They find "energy burden" to be commonly used by social sciences and infrequently used in law, but "energy poverty" to not be used by social sciences and infrequently used by law. While 'energy poverty' appears in the keywords of 26% of publications in this review, 'energy burden' appears in less than 0.5%. These results are further indicative of the under-recognized role that energy poverty, energy justice, and clean cooking research has made to the development of the energy justice field.

An evaluation of author keyword occurrences over time in Figure 1.8 shows that 'energy poverty' not only has a much longer publication history, but remained the most popular author keyword through 2021. The use of 'energy justice' as a keyword only started in 2016, but has grown quickly since.

By applying a clustering algorithm to keywords plus (keywords assigned by WoS machine learning algorithm rather than author keywords) and dividing the time span into several steps, the thematic evolution of the field can be analyzed longitudinally in Figure 1.9. Time steps are divided based on the major turning points in the literature identified in the scientific productivity chart in the years 2010, 2017, and 2020. Then a clustering algorithm of keyword co-occurrence is run at each time step. The longitudinal analysis allows us to highlight the tendencies of topics to merge together, or split into several themes.

Early literature in this energy justice review focused primarily on households and cooking (categorized under energy poverty). These themes merged into focuses on poverty, fuel poverty, and rural electrification in the 2011-2017 time step. New themes such as energy consumption and food security also emerge here. The varied themes of 2011-2017 merge and

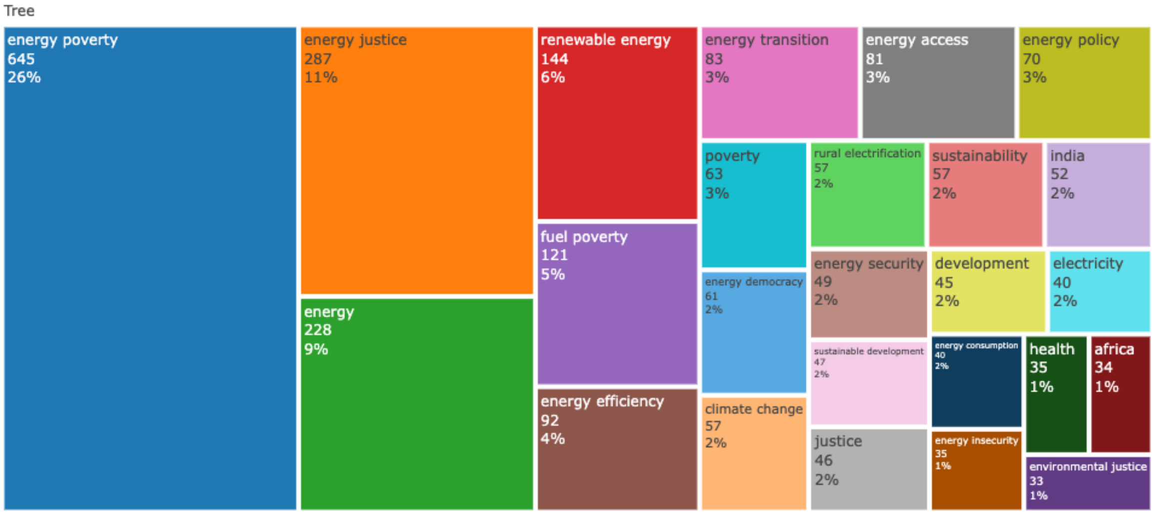

Figure 1.7: Overall frequency of the top 25 keywords listed by authors

are clarified in the 2018-2020 time step into groups labeled electricity, fuel poverty, renewable energy, and policy. Justice only strongly emerges in the last time step that includes 2021 and 2022 but builds out of the literature on renewable energy and policy from 2018-2020. Fuel poverty (aka. energy poverty) is the strongest theme across all time steps, touching nearly all other themes.

Figure 1.10's conceptual structure map uses a multiple correspondence analysis to cluster all publications in the review into 6 groups based on author keyword co-occurrence and a factorial analysis. The origin of the map represents the average position of all articles, therefore the center of the research field. The intuitive literature clusters are clearly separate. For example, the purple cluster represents rural electrification in developing countries, the brown cluster focuses on thermal comfort and buildings, the blue cluster is framework and justice-focused, while the red cluster is health and poverty focused. The brown buildings cluster is farthest from the plot's origin indicating its peripheral nature within the rest of the literature.

Finally, Figure 1.11 combines several earlier approaches to examining this literature using a Sankey diagram. This figure examines the relationship between the intellectual roots of this literature (via references cited, left), the contributing scholars (via most productive authors, center), and the research contents (via keywords, right). The references cited list includes the top ten most locally cited articles explored earlier, as well as the next ten articles. The major contributing authors list displays the top 16 most productive authors, and similarly the research contents list displays the top 13 keywords. Flows between intellectual roots and authors can be interpreted as that author citing that article, with the width representing the

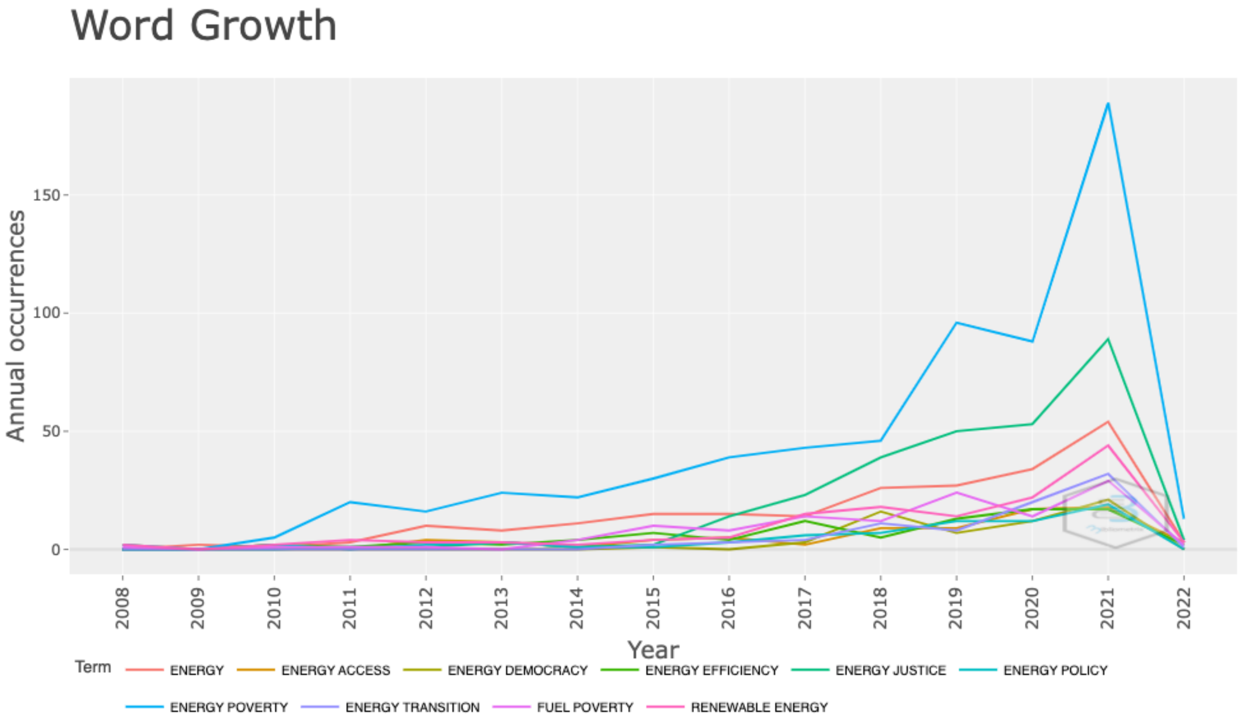

Figure 1.8: Word frequency over time

strength or frequency of citation. Flows between authors and keywords can be interpreted as use of that keyword by that author.

There is frequent co-citation among the authors and intellectual roots indicating significant cross-pollination of knowledge. However, there are notable gaps. For example, while Urpelainen contributes significantly to energy poverty and energy access, their papers are less likely to cite the top energy justice journal articles. This observation supports this chapter's assertion that energy access and energy poverty literature remains distinct from much of the remaining energy justice literature. In contrast, while Liao cites many of the top energy justice references, since their work focuses on energy development and poverty in China, their work remains disconnected from the other top energy justice keywords. Nearly all authors have connections to either the 'energy poverty' or 'energy justice' keywords, with the largest contributions to energy poverty coming from Bouzarovski, Sovacool, and Urpelainen, and the largest contributions to energy justice coming from Sovacool and McCauley.

In summary, this chapter presents the largest and most comprehensive systematic review of the energy justice field to date. Using bibliometric analysis tools, this review covers 2,290 papers published between 1983 and 2022 at a scale appropriate to the number and diversity of publications. The quantitative bibliometric methods are able to review this large and diverse literature in a truly systematic, comprehensive, replicable, and unbiased manner. The energy justice literature has seen rapid growth over its short history and has the potential for large

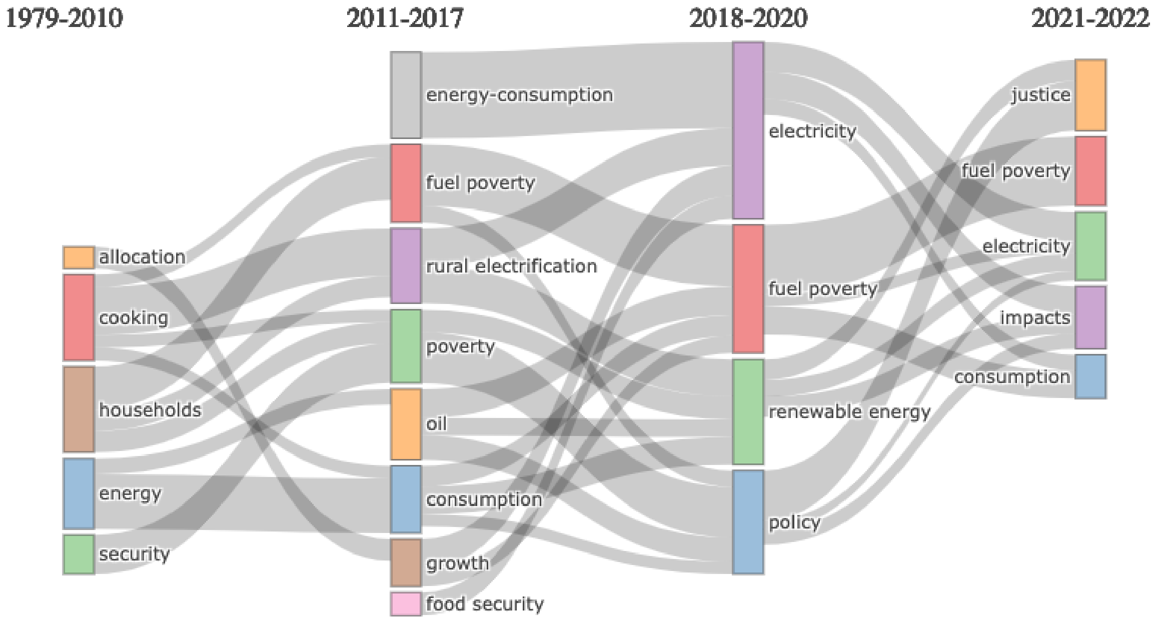

Figure 1.9: Themes trend in energy justice literature

academic and practical impact in the future. It has a multitude of facets, a plurality of theories, and a long dictionary of terminology. However, it remains disjointed and somewhat removed from longer-established social theories of justice. In particular this chapter finds that prior reviews understate the proportion of energy justice literature dedicated to household energy poverty. Energy poverty research in terms of rural electrification and clean cooking have made significant contributions to the field overall in terms of number of papers and intellectual import. Sufficiently recognizing their contributions and integrating the common frameworks, theories, and methods will allow energy justice scholars to build from past literature to reach more universal understandings of energy justice. Doing so will allow the literature to truly contribute towards achieving equity in both the social and economic participation in energy systems while also remediating the burdens of those historically harmed.

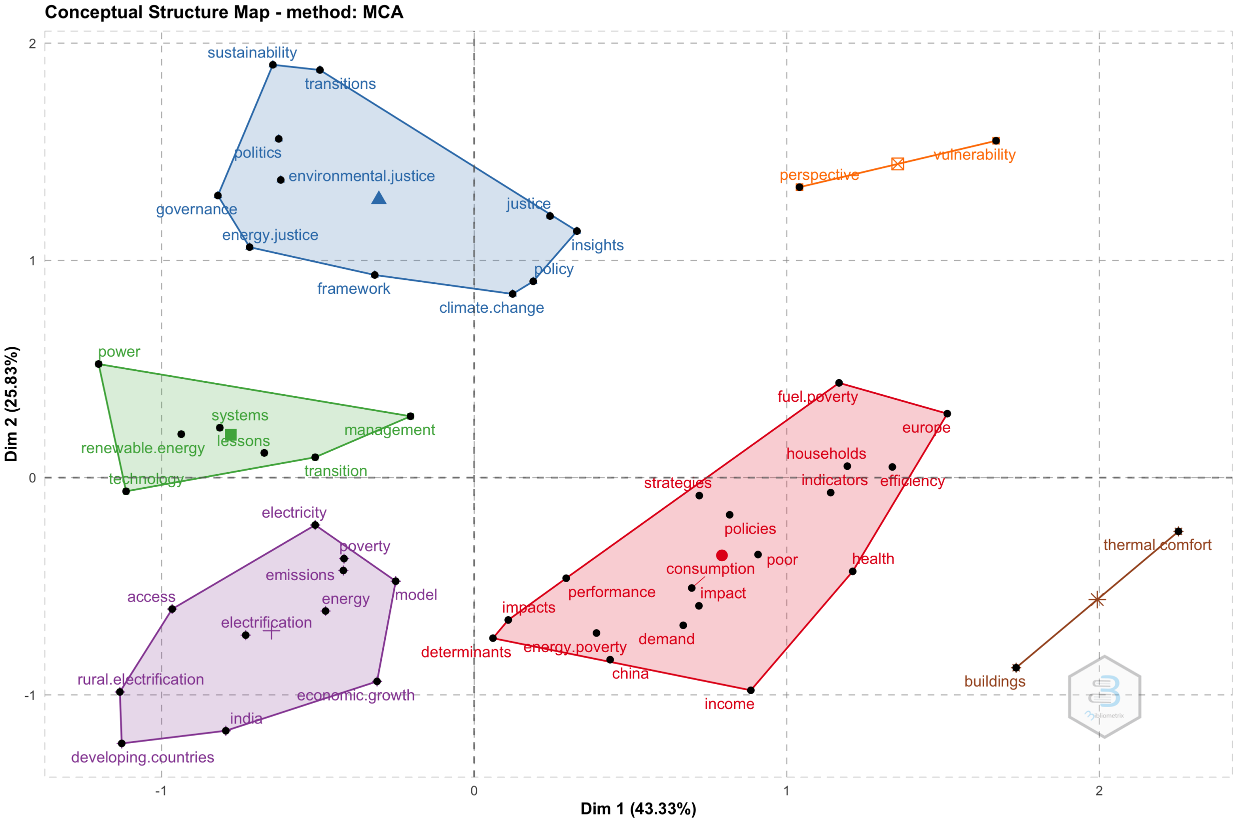

Figure 1.10: Conceptual Structure Word Map on Keywords Plus using Factorial Analysis

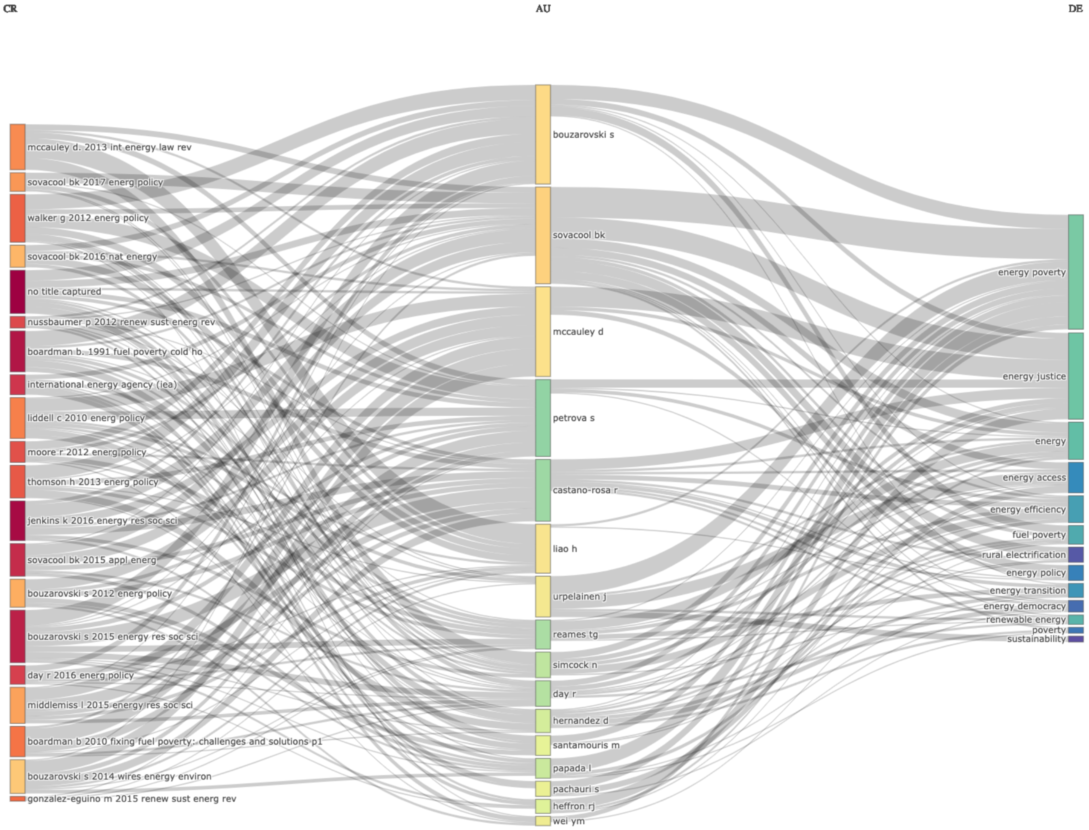

Figure 1.11: Mapping the connections between intellectual roots (reference cited - left), contributors (major authors - middle), and research contents (keywords - right).

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Chapter 2

Theory - Grounding energy justice

Preface

The purpose of this chapter is to ground the research in this dissertation in relevant theory and motivate the applied energy justice approaches I take in Chapters 4, 5 and 6. It ties energy justice theory (as explicitly described in energy justice literature) to broader debates and approaches from other social theory and political philosophy disciplines. While the introductory chapter offers an overview of the history, scope, and landscape of energy justice theory, this chapter presents a specific theory-based tension encountered in my research in this field by exploring the connections between energy justice theory and broader social justice theory. I find that energy justice is incredibly self-referential and rarely cites the well-established social justice and political philosophy theorizations of justice. I systematically measure this gap through in-depth citation analysis and a bibliometric meta-analysis. I then ask what can a more grounded theory base add to the field of energy justice.

2.1 Ungrounded: The philosophical roots of energy justice theory laid bare

Energy justice is inherently social. It is enabled by theories of fairness, disproportionate burdens, and the will to render each their due. One would expect, then, that energy justice theory would be intimately interlinked with and derived from theories of justice from social theory, ethics, and philosophy. However, this not found to be the case. While the energy justice literature publishes theories and frameworks that are intuitively based on justice, it is largely self-referential, producing ‘new’ theories and frameworks rather than applying time-tested theories of philosophical and ethical justice to modern energy issues. This essay reveals the magnitude of this crucial theory gap, and offers perspectives on how justice theory can inform future energy justice literature.

This essay begins by drawing on prior reviews that categorize the use of different theories across the energy justice literature. Prior to Chapter 1 of this dissertation, the most systematic and comprehensive review of the energy justice literature is “The methodologies, geographies, and technologies of energy justice: a systematic and comprehensive review” authored by Jenkins, Sovacool, Mouter, Hacking, Burns, and McCauley in 2021. It examined 155 academic articles published between 2008 and 2019 that included ‘energy justice’ in their title, abstract, or keywords [1]. For each article, they identified the theoretical approach undertaken revealing a wide range as reproduced in Table 2.1. The dominant framework used by articles in their review was that of a three pronged approach of distributional, procedural, and recognition justice, often referred to as the three tenant approach. 38% of articles used all three tenets, an additional 8% used two of the three, and 6% more used a distribution approach for a sum of 52% using any of the three tenets. Strikingly, the next most frequent category (20%) was the absence of an approach, or no explicit approach. Other popular approaches included cosmopolitanism and the eight principles approach. Their results immediately indicate the disjointed nature of energy justice theory.

A review of energy justice literature located in the developing world by Lacey-Barnacle, Robison, and Foulds in 2020 confirms a similar pattern [2]. They include 61 papers that present case studies from ‘developing economies’ or ‘economies in transition’ that include ‘energy justice’, or ‘energy’ and ‘justice’ separately, in their title, abstract, or keywords. Therefore, the 18 primary papers in Lacey-Barnacle et al.’s review would have been included in Jenkins et al.’s global review a year later. Lacey-Barnacle et al. finds an even greater variety of theoretical approaches in their 66-article review than Jenkins et al. does in their 155-article review. The three tenet approach is the most popular well-defined approach, particularly for the review’s primary papers. The secondary papers take quite scattered approaches, but are often informed by broad definitions of environmental justice and climate justice.

After establishing the usage of various theoretical frameworks in energy justice literature, this chapter then investigates their definitions and intellectual underpinnings through close inspections of the two most frequently cited frameworks by publications in Chapter 1’s com-

Approach	**Frequency (%)**
Distribution	6
Distribution and procedure	8
Distribution, procedure, and recognition	38
Universal and particular justice	1
Six principles	2
Eight principles	7
Prohibitive and affirmative	1
Cosmopolitanism	9
Other	8
Not explicit / none	20

Table 2.1: Reproduction of Jenkins et al. (2021) [1] Table 5. Theoretical approaches undertaken within the energy justice literature (n = 155)

prehensive review. In "Energy justice: A conceptual review", Jenkins, McCauley, Heffron, Stephan, and Rehner present a conceptual review of energy justice, proposing the three tenet approach of distributional, recognition, and procedural justice [3]. In "Energy decisions reframed as justice and ethical concerns", Sovacool, Heffron, McCauley, and Goldthau reframe five energy policy problems - nuclear waste, involuntary resettlement, energy pollution, energy policy, and climate change - as justice and ethical concerns. They then propose the eight-principles framework that includes availability, affordability, due process, transparency and accountability, sustainability, intergenerational equity, intragenerational equity, and responsibility. Table 2.3 describes each of these components of justice as defined by the article in which they are proposed.

Jenkins et al.'s 2016 conceptual review in Energy Research and Social Science is the most frequently cited document by the 2,290 publications in Chapter 1's comprehensive review with a total of 276 local citations (12%) [3]. Sovacool et al's 2016 perspective in Nature Energy is the fifth most locally cited article in this review with a total of 120 local citations (5%) [4]. These frequencies are even lower than those found in Jenkins et al. (2021) or Lacey-Barnacle et al. (2020). This indicates that the field overall is either even less likely to use the two most popular frameworks or that these frameworks are assumed to be common knowledge and not cited.

While Jenkins et al. (2016) is the most locally cited article in this review proposing the three-tenets approach [3], the approach was actually originally introduced in 'Advancing Energy Justice: The Triumvirate of Tenets and Systems Thinking' published in 2013 in the

Approach	**Count in Primary papers (n=18)**	**Count in Secondary papers (n=43)**	**Overall Frequency (%) (n=61)**
Other	8	14	36 %
Environmental Justice	1	9	16 %
Distribution, procedure and recognition	9	0	15 %
Social Justice	0	5	8 %
Not explicit / none	0	5	8 %
Sustainability	0	4	7 %
Climate Justice	0	3	5 %
Political ecology	0	3	5 %

Table 2.2: Summarization of Lacey-Barnacle et al. (2020) [2] Tables 1 and 2. Primary and Secondary papers of systematic review. Column: Energy Justice relevant theoretical frameworks (n=61). Listed approaches have more than two papers in either the primary or secondary category.

International Energy Law Review co-authored by McCauley, Heffron, Stephan, and Jenkins [5]. They propose the three tenets in the order of distributional, procedural, and then recognition, while Jenkins et al. (2016) (with the same co-authors plus Rehner) re-orders the tenets to be distributional, recognition, then procedural [3]. Similarly, while Sovacool et al. (2016) is the most locally cited article in this review proposing the eight-principles framework [4], the framework was originally introduced in "Energy justice: Conceptual insights and practical applications" published in 2015 and co-authored by Sovacool and Dworkin [6]. In "New frontiers and conceptual frameworks for energy justice" Sovacool et al. adds two more principles (resistance and intersectionality) to the framework [7]. While the actual number of principles varies across Sovacool's numerous publications, it will be referred to generally as the 'eight principles' approach across this dissertation for ease of understanding.

Upon close inspection, Jenkins et al. (2016) has limited engagement with underlying theories of justice and questionable citations for distributional and procedural justice [3]. However, Jenkins et al.'s does directly engage with Fraser's work on recognition justice. Nancy Fraser is a leading modern philosopher and recognition theorist. In their book "Redistribution or Recognition? A Political-Philosophical Exchange" Fraser debates with the German philosopher Axel Honneth, on the relation of redistribution to recognition. While Honneth conceives recognition as an overarching moral category which encompasses redistri-

Most cited sources	**Tenets or principles**	**Description**
Jenkins et al. (2016) [3] three tenets approach	Distributional	Where are the injustices? Recognizing both the physically unequal allocation of environmental benefits and ills, and the uneven distribution of their associated responsibilities.
	Recognition	Who is ignored? More than mere tolerance, individuals must be fairly represented, free from physical threats, and offered complete and equal political rights.
	Procedural	Is there fair process? Concerns access to decision-making processes that govern the distributions including equitable procedures that engage all stakeholders in a non-discriminatory way.
Sovacool et al. (2016) [4] eight principles approach	Availability	People deserve sufficient energy resources of high quality
	Affordability	The provision of energy services should not become a financial burden for consumers, especially the poor
	Due process	Countries should respect due process and human rights in their production and use of energy
	Transparency and accountability	All people should have access to high-quality information about energy and the environment, and fair, transparent and accountable forms of energy decision-making
	Sustainability	Energy resources should not be depleted too quickly
	Inter-generational equity	All people have a right to fairly access energy services
	Intra-generational equity	Future generations have a right to enjoy a good life undisturbed by the damage that our energy systems inflict on the world today
	Responsibility	All nations have a responsibility to protect the natural environment and reduce energy-related environmental threats

Table 2.3: Description of most common Energy Justice theories Reproduced from Jenkins et al. (2016) Table 1 and Sovacool et al. (2016) Table 2

bution, Fraser argues that the two categories are both fundamental and mutually irreducible [8]. Jenkins et al. includes recognition justice as described by Fraser in their proposed three tenet approach in alignment with McCauley et al. (2013). However McCauley et al. only minimally engages with Fraser directly [5].

A more critical gap in the philosophical roots of energy justice theory is revealed upon examining the sources of distributional and procedural energy justice theory. Rather than directly working with John Rawl's seminal 1971 work 'A Theory of Justice' [9] to define distributional and procedural energy justice, Jenkins et al. cites using a second-hand interpretation of Rawls for these two tenets [3]. Fuller and Bulkeley's 2013 article "Changing countries, changing climates: achieving thermal comfort through adaptation in everyday activities" [10] is used as Jenkins et al.'s basis for a framework that integrates Rawl's ideas of distributional and procedural justice into energy justice. However, Fuller and Bulkeley (2013) never cites Rawls, nor does it include any reference to distributional justice, procedural justice, or justice in general [10]. While the article describes how individual people achieve thermal comfort after a move, it would not be considered as within the core energy, environmental, or climate justice literature and it is not included in the 2,290 publication comprehensive review in Chapter 1.

This critical issue is attributed to be the result of an incorrect citation on the part of Jenkins et al. where they meant to instead cite Fuller and McCauley (2016) "Framing energy justice: perspectives from activism and advocacy" [11]. As described in Chapter 1, Fuller and McCauley (2016) is the tenth most locally cited energy justice article in this 2,290 article sample with 72 local citations (3%). Their article seeks to evaluate the framing of energy justice by activist and advocacy organizations in Philadelphia, Paris, and Berlin [11]. Their analytical framework for exploring activist and advocacy perspectives revolves around two dimensions: i) production and consumption and ii) distribution and procedure. Fuller and McCauley note that their distribution/procedure dimension is inspired by environmental justice research and policy citing Sovacool and Dworkin in 2014 and 2015 as the relevant references [11]. While it is promising that Fuller and McCauley do describe distribution and procedure as it relates to energy justice in depth, Rawls is still never cited directly. It is only through references of the references that any justice theorist or ethical philosopher is mentioned. Sovacool and Dworkin's 2014 book titled 'Global Energy Justice: Problems, Principles, and Practices' does extensively build from John Rawls's theories of justice, and also makes reference to other well-respected justice philosophers such as Plato, Aristotle, John Locke, Emmanuel Kant, Amartya Sen, Ronald Dworkin (unrelated), Martha Nussbaum, and Robert Nozick [12]. Sovacool and Dworkin's 2015 article "Energy Justice: Conceptual insights and practical applications" describes how concepts from justice, philosophy, and ethics can inform energy consumers and producers, interestingly noting that this linkage is "far from obvious" [6]. Even though the article is published in Applied Energy, a journal known for its technical and modeling-focused approach to energy issues, it presents one of the most philosophically grounded energy justice articles available at the time of its publication. In particular, Sovacool and Dworkin's Table 1: Energy justice analytical applications to energy problems, is reproduced below which is itself reproduced from Sovacool and Dworkin (2014) [12]. While the energy justice field's generally-recognized definitions of the most pertinent energy topics and their relevant injustices has evolved significantly since 2014, the general framework remains useful.

Topic	**Concept**	**Major philosophical influences**	**Applications to energy**	**Injustices**
Energy efficiency	Virtue	Plato and Aristotle	Energy efficiency: high penetration of efficient service	Inefficiencies involved in energy supply, conversion, distribution, and end-use
Energy externalities	Utility	Jeremy Bentham, John Stuart Mill, Henry Sidgwick	Wellbeing: less suffering, pain, externalities, and disasters associated with energy production and use	The imposition of negative social and environmental costs on society such as traffic congestion, the extractive industries affiliated with energy production, the resource curse, nuclear waste, air pollution, greenhouse gas emissions, and water consumption
Human rights and social conflict	Human rights	Immanuel Kant	Universal human rights: an obligation to protect human rights in the production and use of energy	The violation of civil liberties—in some extreme cases death and civil war—undertaken in pursuit of energy fuels and technology, as well as the contribution of energy production to military conflict
Energy and due process	Procedural justice	Edward Coke, Thomas Jefferson, Jürgen Habermas	Due process: free prior informed consent for the siting of energy projects; fair representation in energy decision-making	Approaches to energy siting that ignore or contravene free, fair, and informed consent, and/or do not conduct adequate social and environmental impact assessments

Energy poverty	Welfare and happiness	John Rawls, Amartya Sen, Martha Nussbaum	Accessibility and subsistence: an energy system that gives people an equal shot of getting the energy they need, energy systems that generate income and enrich lives	Lack of access to electricity and technology, dependence on traditional solid fuels for cooking, and time-intensive fuelwood and water collection and processing of food in emerging economies, borne mostly by women and children
Energy subsidies	Freedom	Robert Nozick, Milton Friedman	Libertarianism: energy decisions not unduly restricted by government intervention	Gross subsidies that involve an involuntary wealth transfer to recipients, essentially raiding the pocket books of the unwilling
Energy resources	Posterity	Ronald Dworkin, Brian Barry, Edith Brown Weiss	Resource egalitarianism: an obligation to minimize resource consumption and ensure adequate reserves for future generations	Exhaustion of depletable energy reserves and fuels
Climate change	Fairness, responsibility, and capability	Peter Singer, Henry Shue, Paul Baer, Stephen M. Gardiner, Dale Jamieson, Simon Caney	Intergenerational equity: and obligation to protect future generations from energy-related harms	A daunting suite of negative impacts from climate change including ocean acidification, food insecurity, climate refugees, and the increased frequency and severity of natural and humanitarian disasters

Table 2.4: Energy justice analytical applications to energy problems. Reproduced from Sovacool and Dworkin (2014 and 2015) [6, 12]

These investigations serve to show that the intellectual roots of the most widely cited energy justice theory framework are four levels of documentation down. All intermediate layers of articles cite themselves or other energy justice scholars rather than directly cite any social theorist or justice philosopher and their widely-regarded seminal works on justice theory. The distribution of burdens and benefits and the pertinent procedures are rather intuitive ways for scholars with technical backgrounds to study specific energy justice concerns. However, the stark disconnect between energy justice theory and fundamental theories of justice from ethics, law, social theory, and philosophy is a critical issue for the field to resolve.

As noted above, Sovacool has such a large body of publications, many of which do directly engage with concepts from justice and ethics, that it is more difficult to make conclusive statements. Because Sovacool et al. (2016) 'Energy decisions reframed as justice and ethical concerns' is the most cited version of the eight-principles approach, this chapter focuses on what is most used by other literature. The article starts by describing five energy problems - involuntary resettlement, fossil fuel pollution, energy poverty, nuclear waste, and climate change - as pressing justice concerns violating notions of procedural justice, human rights, distributive justice, intergenerational justice, and global responsibility, respectively [4]. Each energy issue's relevant justice concept is broadly described with references to relevant justice theorists but only to the extent that it is relevant to that specific energy issue. Finally, the eight-principles energy justice decision-making framework is described in that article's Table 2. However the eight-principles are not inclusive of the justice concerns described earlier in the article, and there is no justification for choosing these specific eight principles over other possible principles. In summary, 'Energy decisions reframed as justice and ethical concerns' integrates concepts from justice as ethics, but only in a selective manner. It does not comprehensively examine what the breadth of justice theory can contribute to how academia conceptualizes and examine energy justice.

To further quantify the philosophical roots of the entire energy justice literature, this chapter draws on the comprehensive bibliometric review of energy justice detailed in Chapter 1. For all 2,290 articles, all cited references are examined, selecting only references published by philosophical thinkers and social theorists listed in two respected philosophical references: The Stanford Encyclopedia of Philosophy and InPhO (the Internet Philosophy Ontology project). The 91,291 individual cited references from the 2,290 publication review are searched for any author listed in the bibliography of the Stanford Encyclopedia of Philosophy entry on Justice [13], and any of the top thirty related thinkers listed on InPhO's entry on justice. The four authors listed below in Table 2.5 are the only philosophical thinkers from either reference that had more than 0.7% of the energy justice literature in this review cite them as a reference.

The most cited theorist is Amartya Sen in terms of the number of documents referenced, and the number of articles that cited each reference. In particular, literature on energy poverty often cited the seminal 1999 work, Development as Freedom. However no additional theorist found in the InPhO list of related thinkers that was not in the Stanford Encyclopedia was found in the reference list. Therefore, less than 15 articles in the 2,290 review directly cited each of Plato, Aristotle, Socrates, Immanuel Kant, David Hume, Thomas Hobbes, G.A. Cohen, John Locke, John Stuart Mill, Robert Nozick, T.M. Scanlon, Henry Sidgwick, etc, in their bibliography. Less than 12% of articles cited at least one of: J. Rawls, A. Sen,

Theorists	**N. Citations**	**Popular References**
Amartya Sen	171	1976, Poverty: An Ordinal Approach to Measurement [14]
		1985, Commodities and Capabilities [15]
		1992, Inequality Reexamined [16]
		1993, The Quality of Life [17]
		1999, Development as Freedom [18]
		2009, The Idea of Justice [19]
Nancy Fraser	73	1997, Justice Interruptus: Critical Reflections ... [20]
		2000, Rethinking Recognition [21]
		2003, Redistribution or Recognition? ... [8]
John Rawls	70	1971, A Theory of Justice [9, 22]
		1993, The Law of Peoples [23]
		2001, Justice as Fairness: A Restatement [24]
Martha Nussbaum	65	2000, Women and Human Development: Capabilities [25]
		2003, Capabilities as Fundamental Entitlements: Sen ... [26]
		2011, Creating Capabilities: Human Development ... [27]
Total	256	

Table 2.5: Justice theorists and philosophers cited by articles in this energy justice review

N. Fraser, M. Nussbaum, R. Dworkin, T. Scanlon, R. Nozick, J.S. Mills, T. Hobbes, G.A. Cohen, or J. Locke.

It is acknowledged that the above analysis is limited to western philosophy and ethics, excepting Amartya Sen's The Idea of Justice that bridges western-Rawls and eastern-Hindu theories of justice. However, en masse, energy justice is dominated by western approaches. Publications such as the book 'Energy Justice Across Borders' [28], or the articles 'New frontiers and conceptual frameworks for energy justice' [7], 'Energy development and Native Americans: Values and beliefs about energy from the Navajo Nation' [29], and 'The temporalities of energy justice: Examining India's energy policy paradox using non-western philosophy' [30] attempt to fill this gap by integrating non-western approaches such as African 'ubuntu' ethics, Confucianism, Indigenous American perspectives, or the Hindu Bhagavad Gita into modern energy justice approaches. The continuing development of non-western philosophical approaches is encouraged, particularly when they inform local energy justice issues in the part of the world where the approach derived.

Through this investigation of the philosophical roots of modern energy justice literature, severe disconnects and gaps were revealed. There is a proliferation of new conceptual frameworks, but rarely are the frameworks thoroughly embedded in the underlying philosophical and ethical theories of justice. Further, there is a lack of common definitions for even the most common justice terms. Humans have spent thousands of years developing, critiquing, scrutinizing, and evolving theories of ethics and justice. Individual scholars have spent lifetimes developing theories of inequality, poverty, and racial justice. The comprehensive aims of energy justice will fail to take shape if the field continues to neglect the potential contributions that justice theory can make to energy justice.

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Chapter 3

Methods - Quantitative approaches and their theoretical bases

Preface

Motivating the application of justice principles to specific energy justice issues in Chapters 4-6, this chapter explores the diverse quantitative methods used in research on distributive energy justice. It explains the reasoning behind choosing these methods and the perceived advantages and disadvantages of using these methods to study questions of justice. In particular this chapter attempts to create a clearer distinction between equality and equity. I ask what functional forms of equality and equity are appropriate, and what does making the different function forms of distributional justice explicit imply for future energy justice research. In doing so, it identifies ways in which various quantitative methods can be used separately, or in combination, to provide a more comprehensive perspective on justice considerations.

3.1 A review of distributive energy justice theory

This dissertation uses The Energy Justice Workbook's definition of energy justice which states that "Energy justice refers to 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]. This definition makes explicit that the goal is to achieve equity through justice, not equality. However, many quantitative approaches to energy justice fail to make this distinction. The essay attempts to clarify equity from equality by delving into distributive justice theory, asking what functional forms of equality and equity are available and appropriate for distributional energy justice, and what does making these forms explicit imply for future energy justice research.

The three-tenet approach proposes distributional, recognition, and procedural justice as key branches for energy justice to evaluate [2]. While recognition and procedural justice are less amenable to quantitative evaluations, distribution is particularly well-suited.

Rather than a single definition, the Stanford Encyclopedia of Philosophy describes distributive justice broadly as a topic composed of many competing principles that determine morally preferable distributions of benefits and burdens across members of a society. "Distributive principles vary in numerous dimensions. They vary in what is considered relevant to distributive justice (income, wealth, opportunities, jobs, welfare, utility, etc.); in the nature of the recipients of the distribution (individual persons, groups of persons, reference classes, etc.); and on what basis the distribution should be made (equality, maximization, according to individual characteristics, according to free transactions, etc.)" [3].

The breadth of energy justice literature examines the distribution of many different energy benefits and burdens including but not limited to residential rooftop solar deployment [4, 5], household energy efficiency [6], the burden of energy bills [7, 8], power plant and toxic waste siting [9], and electricity reliability [10–12] to which Chapters 5 and 6 of this dissertation specifically add.

This remainder of this chapter focuses on the breadth of methods for investigating the basis of distribution. In 'The Idea of Justice', Amartya Sen explores the plurality of impartial reasons, or the problem that there can be multiple and "competing reasons for justices, all of which have claims to impartiality and which nevertheless differ from - and rival - each other" [13]. Through the example of three children and a flute, each of three children could make reasonable objective claims to the one flute on the grounds of either economic egalitarianism, libertarianism, or utilitarianism. However, distribution according to one method would be considered unjust by another. In terms of energy justice issues, there are also multiple competing forms of objective distributions, however some are morally preferable over others. A selection of common distributive principles from philosophy [3] applied to energy justice are in Table 3.1.

Rather than working from existing energy justice issues and finding a relevant ethical principle, as is done by prior energy justice literature that integrates concepts from philosophy only as relevant, this chapter presents a novel approach that takes a holistic perspective of philosophical theories as its core.

Chapter 4 of this dissertation discusses how gender mediates access to the benefits of rooftop solar energy access in rural Tanzania thereby taking a feminist critique. This chapter operationalizes its concept of energy justice by comparing two modes of distribution inspired by the above principles. Specifically, this chapter draws on the contributions of two of the most influential political philosophers of the 20th century, John Rawls and Amartya Sen.

1. A primary goods approach in which every individual has a minimum level of said good, inspired by John Rawls's difference principle interpretation of egalitarianism in 'A Theory of Justice' [14]. This is to say effectively to each in equal parts – referred to as equal.

2. A capabilities approach in which every individual receives according to the level needed to enable the individual to achieve equivalent capability, inspired by Amartya Sen's approach to equality of opportunity in 'The Idea of Justice' [13]. This is to say to each according to need – referred to as equitable.

As an example, while an energy access approach that prioritizes equality may value equal access to, usage, and impact of off-grid solar, an equity approach would account for the disproportionate burden felt by electricity's absence. Women and low-income households are most impacted by energy poverty, and therefore stand to gain the most from access. Equal and equitable both stand distinct from the welfare-based utilitarian approaches which are prone to reproducing existing gender and class-based social power asymmetries.

Distributive Principle	**Definition in [3] applied to energy**	**Example in energy justice literature using or critiquing the principle**
Strict egalitarianism	The allocation of equal energy benefits and burdens to all members of society (equality of outcome)	Expecting equal rooftop solar deployment or electricity reliability
John Rawls' Difference Principle [14]	Egalitarian distribution of energy benefits and burdens except for when the inequalities in question would make the least advantaged members of society better off than they would be under strict equality	Ch 6's policy recommendation to exclude the most vulnerable communities from receiving rotating outages
Equality of Opportunity and Luck Egalitarianism	Equality of opportunity (rather than outcome). When in combination with another principle, inequalities are permitted by the overall theory when people have equal opportunity to achieve greater or lesser amounts of energy goods or burdens. Opportunity defined by factors for which an individual can reasonably be held responsible (not race, gender, age, etc.)	Modern Energy Minimum proposals that guarantee a basic set of energy services to overcome unequal resource endowments for energy access
Welfare-based (utilitarianism)	Energy goods and burdens should be distributed to maximize a society's welfare. The choice of a welfare function, the inclusion of individual preferences, and interpersonal comparisons are of primary importance	When utility is defined as willingness to pay, any market-based process for distributing energy benefits or burdens
Desert-based	Individuals should be rewarded for their contribution, effort, or the costs they occur in an activity. Rarely a complete set of distributive principles	Equitable wages across diversity in the energy workforce
Libertarianism	A distribution is just if everyone is entitled to the energy goods they possess under the distribution whether through legitimate acquisition or transfer	A community's claim to their own land when threatened by displaced by large-scale energy projects, whether fossil fuels, hydro, or wind
Feminist critiques	Distinctive versions of other theories that ask what, if any, the practical experience of gender makes to the subject matter or study of justice	Ch 4's examination of gender's mediating effect on the benefits of solar energy access

Table 3.1: Distributive principles of justice described in Lamont and Favor (2017) [3] as applied to energy justice

Income	$\Leftrightarrow$	**Electricity reliability**
number of individuals in the population	n	number of individuals on the electricity system
expenditure or income of person i	y_i	hours of power outage of person i
total expenditure of the population	Y	total hours of customer outages on system
average expenditure in the population	$\mu = \frac{Y}{n}$	average hours out on the system

Table 3.2: Translating income inequality metrics to reliability inequality metrics

3.2 A review of quantitative energy justice approaches

After establishing the theoretical bases for different modes of distribution in the previous section, this section examines the various functional forms, noting their strengths and weaknesses.

This chapter separate approaches into two categories. First, approaches that examine the equality of the distribution of energy justice concerns are detailed. These therefore rely on an egalitarian energy justice philosophy and are positive in the sense that they make no explicit use of any concept of social welfare. Included second are approaches that examine equity of energy justice. This chapter leans primarily on an equality of opportunity or capabilities philosophy of equity, making normative claims of social welfare and the loss incurred by unequal distributions.

In line with energy poverty literature, this section draws extensively on development economic theories of income and poverty for a comprehensive perspective on relevant metrics. In particular this chapter draw from de Janvry and Sadoulet's 2016 textbook titled 'Development Economics: theory and practice', particularly Chapter 6: Inequality and Inequity, Sen's 1973 book titled 'On Economic Inequality', particularly Chapter 2: Measures of Inequality [15, 16], and Clarke and Cooke's A Basic Course in Statistics, Third edition [17]. However, rather than describe the following quantitative approaches in terms of income as is the case in their source documents, this chapter interprets and applies them to energy burdens examined in this dissertation, namely the reliability of electricity in terms of yearly hours of outages, or SAIDI. This translation also moves from examining inequalities in a benefit (more income) to inequalities in a burden (hours of outage). The translation and the appropriate notation is described in Table 3.2:

Egalitarian / Equality / Positive Approaches

The follow positive measures make no explicit use of social welfare. They are meant only to examine inequalities as viewed through an egalitarian approach where energy benefits and burdens should be allocated equally among all members of society.

Range

Range is defined as the span between the extreme values of the distribution. Occasionally it is described as a ratio of the mean.

$$range = max(y_i) - min(y_i) \tag{3.1}$$

- *Pros*: simplest measure of inequality
- *Cons*: ignores the distribution between the extremes therefore relatively uninformative for large sets of data, does not have more extended mathematical properties

Variance and Standard deviation

Variance measures how closely observations of household outage hours cluster around the mean of the electricity system. More precisely, it measures the average of the squared deviations from the mean.

$$V = \frac{1}{n}\sum_{i=1}^{n}(y_i - \mu)^2 \tag{3.2}$$

The standard deviation is a closely related measure of variability, but that is expressed in the same units of the observations. Formally, it is the positive square root of the variance.

$$\sigma = \sqrt{V} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \mu)^2} \tag{3.3}$$

- *Pros*: the most common measures of variability, Standard deviation is in the same units of observations
- *Cons*: Variance is measured in units of x^2 therefore hard to interpret and compare, not scale invariant
- *Usage in energy justice literature*: Heylen et al. (2019) describes the application of standard deviation to fairness in power system reliability [10]

Coefficient of variation

The coefficient of variation measures inequality as the standard deviation of outage hours per unit of average outage hours.

$$CV = \frac{\sigma}{\mu} \tag{3.4}$$

- *Pros*: unit-free, additively decomposable across subgroups, scale invariant
- *Cons*: not defined on a zero-to-one scale
- *Usage in energy justice literature*: Heylen et al. (2019) describes the application of the coefficient of variation to fairness in power system reliability [10]

Lorenz Curves and Gini coefficient

As explored further in Chapter 5, a Lorenz curve plots the cumulative share of the population on the X-axis against the cumulative share of outage hours on the Y-axis. A perfectly equal share of outage hours across a population results in a line with a slope of one. The greater the inequality in the sample, the more the curve bows down to the X-axis.

The Gini coefficient is defined as the ratio of area A (between the 45-degree line and the lorenz curve) to area A+B (where B is the area between lorenz curve and outer box). Scale 0 (complete equality) to 1 (maximum inequality). Also equal to covariance between outage hours and rank across observations times $2/n * \mu$.

$$G = \frac{A}{A+B} = \frac{2}{\eta\mu} cov(y, r), 0 \leq G \leq 1 \tag{3.5}$$

While the Gini coefficient cannot be decomposed across subgroups, it can be decomposed by outage sources. While the Gini can't be broken down to say whether there is more within-group or between-group inequality in outage hours, it can tell how much of the inequality in outage across the whole energy system measured by the Gini index comes from different outage sources.

If there are $(k = 1, ..., K)$, sources of outages, each contributing y_{ik} to the total hours y_i of household i, with $\sum_k y_{ik} = y_i$, the decomposition of the total Gini is given by:

$$G = \sum_k w_k R_k G_k \tag{3.6}$$

where μ is the mean outage hours; μ_k is the mean outage hours from source k; w_k is the weight of the outage source in mean outage hours $= \mu_k/\mu$; r_k is the within source household rank; r is the overall household outage hours rank; the relative correlations $R_k = cov(y_k, r)/cov(y_k, r_k)$; G is the overall Gini; and G_k is the Gini of outage source k. Therefore the share of outage source k in total inequality is equal to $w_k R_k G_k / G$

- *Pros*: the most frequently used measure of inequality, trasparent graphical representations, easily interpretable and comparable, decomposable by source. Better than variance for skewed distributions, best at characterizing differences in the middle of the distribution
- *Cons*: two Lorenz curves that cross can have the same Gini, not good at characterizing differences at the extremes of distributions, not additively decomposable across subgroups

- *Usage in energy justice literature*: Jacobson et al. (2005) applies Lorenz curves and Gini coefficients to electricity consumption across countries [18]. Heylen et al. (2018a, 2018b, and 2019) applies Lorenz curves and Gini coefficients to examine the fairness of electricity outage distribution in a power system [10, 19, 20]. Tong et al. (2021) applies the Gini coefficient to measure inequality of energy consumption [21]

Theil entropy index

The Theil entropy index runs from 0 (perfect equality) to ln(n) (maximum inequality)

$$T = \sum_{i=1}^{n} \frac{y_i}{Y} ln(\frac{ny_i}{Y}) \tag{3.7}$$

Decomposition across k subgroups of the population ($j = 1, ..., k$), would be:

$$T = \sum_{j=1}^{k} \frac{y_i}{T_j} + \sum_{j=1}^{k} y_i ln(\frac{y_i}{m_j}) \tag{3.8}$$

where y_j is the outage share of group j, m_j is the population share of that group, and T_j is the Theil entropy index for group j. The first term describes within-group inequality, while the second term describes between-group inequality. This therefore tells us how much of total inequality is due to within-group as opposed to between-group inequality and can inform appropriate policy steps.

- *Pros*: additively decomposable
- *Cons*: cannot be used if there are negative values (more relevant for other energy burdens), slightly arbitrary and not intuitive

Shares and Kuznets ratios

Shares, also known as interquantile ratios or disparity ratios, describe proportions of total outage hours held by certain groups: for example, what share of total outage hours is held by 20 percent of the population with the highest numbers of outage hours. The choice of group thresholds depends on the analysis.

Kuznets ratios give ratios between different shares. For example, the ratio of the 20th percentile share to 80th percentile share.

$$20/20 \ ratio = \frac{percentage \ of \ Y \ experienced \ by \ highest \ 20\%}{percentage \ of \ Y \ experienced \ by \ lowest \ 20\%} \tag{3.9}$$

- *Pros*: interpretable, useful for characterizing extremes
- *Cons*: not as useful in the middle of distributions

- *Usage in energy justice literature*: Tong et al. (2021) applies the disparity ratios to measure inequality of energy consumption [21]. Heylen et al. (2018, 2019) describe the application of disparity ratios to fairness in power system reliability [10, 19]

T-Tests

Under a certain set of conditions, a t-test can be used to determine if the means of two sets of data are significantly different from each other. Several of these assumptions include: that the means of the two populations follow normal distributions and they are sampled independently. Chapter 6 uses Welch's t-test to compare the mean values of two populations when the variances and sample sizes of the two populations are not assumed to be equal. The equation for a Welch's t-test is:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sigma_{\bar{\Delta}}} \tag{3.10}$$

$$where \sigma_{\bar{\Delta}} = \sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \tag{3.11}$$

- *Pros*: Provide a degree of certainty surrounding if the observed differences in hours of outages are due to random chance or not
- *Cons*: Need to satisfy the assumptions of normality, sample size, and independence for properly interpreting results. P-values are often subject to p-hacking where many possible associations are tested. Does not take into account the evaluation of bias and confounding.
- *Usage in energy justice literature*: See Chapter **??**: Leaving communities of color in the dark.

Capabilities / Equity / Normative Approaches

The follow normative measures are based on an explicit formulation of social welfare and the loss incurred from unequal distributions.

Dalton's measure

Based on a utilitarian framework, Dalton's measure compares actual levels of aggregate utility and the level of total utility that would be obtained if outage hours were equally divided. The measure describes the ratio of actual social welfare to the maximal social welfare, taking utility levels to be all positive.

$$D = \frac{\sum_{i=1}^{n} U(y_i)}{nU(\mu)} \tag{3.12}$$

- A utilitarian maximization function that takes the ratio of actual social welfare to the maximal social welfare. All utility levels are considered positive. Uses a concave utility function with diminishing marginal utility of income.
- *Cons*: not invariant with respect to positive linear transformations of the utility function

Atkinson's measure

Building on Dalton's measure, Atkinson's measure defines 'the equally distributed equivalent' energy burden of a given distribution of energy burdens. In other words, the measure is defined as the level of per-capita burden allocated to everyone that would make total welfare exactly equal to the total welfare generated by the actual burden distribution. With y_e as this 'equally distributed equivalent':

$$y_e = \frac{y}{nU(y)} = \sum_{i=1} nU(y_i) \tag{3.13}$$

Atkinson's measure of inequality is

$$A = 1 - (\frac{y_e}{\mu}) \tag{3.14}$$

- *Pros*: lies between 0 and 1
- *Cons*: highly sensitive to the choice of utility function and definition of social welfare
- *Usage in energy justice literature*:

Quadrant analyses

Tong et al. (2021) developed a quadrant approach to quantify and prioritize energy program outreach and investments across census block groups [21]. Their method bins all census block groups in a city into four quadrants based on pairs of variables chosen to reflect their three goals of:

1. community-wide carbon mitigation
2. reducing energy burden
3. reducing social inequality by race and income

with quadrant cutoffs established at each variable's average.

- *Pros*: allows stakeholders to visualize identify, quantify, and prioritize equity investments relative to multiple goals
- *Usage in energy justice literature*: Tong et al. (2021) [21].

Correlation with markers of vulnerability

This approach first leans on other literature to define vulnerability, and then uses statistical approach such as regressions to measure correlations between markers of vulnerability and increased energy burdens or benefits. For example Chapter 6 of this dissertation relies on Thomas (2019) to define reduced adaptive capacity and increased vulnerability to harm from climate change. Thomas (2019 finds increased vulnerability among U.S. non-white populations, those with lower-incomes or in poverty, women, the uneducated, those linguistically isolated, and the disabled [22]. C

This approach has been quite common in other recent quantitative energy justice publications. For example, Sunter et al. (2019) uses the LOWESS (locally-weighted scatterplot smoothing) method to fit local linear relationships between household income and rooftop PV adoption among different racial and ethnic majority census tracts [5]. Reames (2016) uses the ordinary least square method to analyze how housing unit and housing characteristics influence residential heating energy efficiency using bivariate and multivariate analyses. The then apply a logistic regression to examine how the proportion of racial/ethnic minority headed households, and other census block group socio-economic characteristics affected the probability of energy vulnerability [6]. Finally, Brockway et al. (2021) use multiple geospatial, regression, and machine learning techniques to evaluate grid infrastructure limits that result in inequitable access to future distributed energy resources in California [23].

- *Pros*: can more actively incorporate explicit measures of welfare alongside the distribution of energy benefits and burdens than other listed approaches
- *Cons*: its strength depends upon the appropriateness of the choice of regression to measure correlation, Can be subject to p-hacking, does not necessarily investigate the drivers behind inequities
- *Usage in energy justice literature*: As noted above, see Chapter 6: Leaving communities of color in the dark, Sunter et al. (2019 [5],

In summary, this chapter has reviewed the philosophical bases for distributive energy justice, and formalized the quantitative methods for operationalizing distributive energy justice comparisons. In turn, the field must ask itself three questions: What set of impartial reasoning are used to determine energy justice? Are the methods appropriate to the chosen philosophical principles and goals? And if not, what remediation approaches are available?

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Part II

Praxis

Chapter 4

Equal, but not equitable? A gender-differentiated study of off-grid solar in rural Tanzania

Preface

The first application chapter applies mixed methods to examine how gender mediates access to the benefits of off-grid solar in Tanzania.

A large and present energy justice burden in much of Sub-Saharan Africa is the lack of access to electricity. Further, women and low-income households experience a disproportionate share of this burden. Decentralized off-grid solar systems have played a prominent role in providing access to the benefit of lighting services to date, particularly in Tanzania. However, many electrification plans - whether through off-grid solar or national grids - are gender and poverty-agnostic. Drawing on quantitative surveys and qualitative interviews in a mixed-methods approach, this chapter asks how the distributional benefits of solar are mediated by gender and class in rural Tanzania.

This chapter thereby investigates inequities in access to the benefits of solar electrification across gender. This research use a feminist critique and compare the operationalizations of two competing theories of energy justice: an egalitarian approach that values equal distribution of benefits and a capabilities approach to measure equity.

The work in this chapter was submitted for publication as an article titled "Equal goods, but inequitable capabilities? A gender-differentiated study of off-grid solar energy in rural Tanzania." It is included in this dissertation with permission of my co-authors Annelise Gill-Weihl and Daniel M. Kammen.

Abstract

Women and low-income households experience a disproportionate burden of energy poverty. Despite this, many electrification plans insufficiently address gender and low-income households. Off-grid solar has and will continue to play a role in expanding access to electricity in rural Sub-Saharan Africa; however, off-grid solar is rarely examined across genders. This research draw on quantitative surveys and qualitative interviews from a case study in rural Tanzania to investigate the energy justice implications of off-grid solar. This chapter ask how the distributional benefits of solar are mediated by gender and class, filling a key gap in the literature of off-grid solar's impact. Little evidence of gender differentiation is found, suggesting equality within off-grid solar usage, but not equity. Solar remains out of reach for low-income households. In this case study, off-grid solar is used both as a primary source for low-and-middle-income households, and as a back-up source for middle-and higher-income households. Solar is found to be under-used as a means of income generation and that payment schemes may not be the key to achieving energy justice. Further work is needed to ensure that women and low-income households have not only equal, but equitable access to the benefits of off-grid solar.

4.1 Introduction

Sustainable Development Goal 7 (SDG7) calls for "universal access to affordable, reliable, sustainable, and modern energy services" [**noauthor˙tracking˙2021**, 1]. Until it is achieved, women and low-income households carry a disproportionate burden of energy poverty and lack of services. These burdens materialize prominently as higher air pollution exposure for women [2] and a higher percentage of incomes spent on fuel for low-income households [3]. These disproportionate burdens are core motivating factors for the theoretical and practical pursuit of universal energy access. Additionally, the United Nations describes energy access as the 'golden thread' linking and enabling at least nine of the SDGs including eradication of poverty, gender equality, and increased work and economic growth [4].

Although providing the level of service currently only provided by high-quality grids is the ultimate goal, decentralized systems – such as mini-grids, solar home systems (SHS), and intra-household solar lanterns – represent a vital interim level of access. Decentralized systems have played a prominent role in providing electricity access to date, particularly in East Africa [**noauthor˙tracking˙2021**]. Least-cost electrification models project that they will play an even larger role in the future [5]. The International Energy Agency (IEA) projects that 55% of the population lacking access will gain electricity access through mini-grids (30%) or stand-alone systems (25%) [5].

Despite this, much of the grey and peer-reviewed scholarship of off-grid solar's access, usage, and impact is rarely differentiated by gender [6–8]. Anditi et al. 2022 suggests a gender-analysis framework for energy policy in Africa, but only for urban informal settlements [9]. Even gender-positive approaches of utility-scale solar in India have been found, in reality, to disempower women and exacerbate economic exclusion [10, 11]. As solar[1] plays a growing role in rural electricity access worldwide, studies evaluating its energy justice implications will gain importance.

Therefore, this chapter investigates the energy justice implications of off-grid solar in relation to gender and low-income households using a case study in rural Tanzania by asking: "How do categories of gender and social class shape the use of energy generated from off-grid solar technologies at the household level?"

In Tanzania, 77 % of the population lacks direct access to electricity [2], placing it among the top twenty access-deficit countries. The provision of access in Tanzania is keeping pace with population growth [**noauthor˙tracking˙2021**], but rapid improvement is needed in order to meet SDG7's goal of universal access by 2030. Despite Tanzania's focus on expanding the national grid, investment in solar continued to rise, particularly between 2014-2017 during drought-related power outages [13]. Overall, the 2017-2018 Tanzanian Household Budget Survey found that 29 % of the population uses the national grid as their main lighting source, while 26.5 % uses solar. This leaves 55.5 % of the population relying on torches (rechargeable lamps), kerosene, candles, paraffin, etc.[3] This case study focuses on a rural town, Shirati, located in the Mara Region, where in 2017-2018, 20.7 % of the population used the national grid as their main lighting source and 26.6 % used solar [14].

Despite the prominence of solar in Tanzania, there are few ethnographic articles on gender and off-grid energy in Tanzania. These works find energy to be a "relational and gendered configuration of people, nature, labor, and sociality that makes and sustains human and natural life" [13](pg.71) and document the tumultuous, and unjust, relationship between rural, low-income customers and the solar energy companies [15]. This case study, set in rural Tanzania, builds off this emerging work and adds through further quantitative surveys and qualitative interviews and observation to the growing body of energy justice literature on off-grid solar, specifically regarding gendered and low-income access. This chapter fills a key gap by evaluating how the distributional benefits and burdens of off-grid solar are mediated by gender and class, specifically within a rural setting in Tanzania.

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[1] When 'solar' appears in this text without qualifiers, it refers to off-grid, home-scale, paneled, solar systems rather than grid-connected systems or pico-solar products such as solar lanterns. 'Off-grid solar' or 'SHS' can be interpreted as equal to 'solar'

[2] The IEA defines access to electricity, as "a household having access to sufficient electricity to power a basic bundle of energy services - at a minimum, several lightbulbs, phone charging, a radio and potentially a fan or television - with a level of service capable of growing over time" (pg. 1), but practically measures it as a grid connection or stand-alone system that provides the above basic energy bundle [12]

[3] Note, diesel generators were not considered in the survey. However, the "other" category comprised only 1 % of the population.

4.2 Off-grid solar

The off-grid solar market has rapidly expanded in the last ten years to provide lighting to millions across low- and middle- income countries, particularly in Sub-Saharan Africa, and is expected to expand to 823 million users by 2030 [16]. Products range from pico-solar lanterns to high-capacity SHS, but lanterns represent the majority of sales (83%) [16].

The World Bank's Energy Sector Management Assistance Program (ESMAP) developed a Multi-Tier Framework (MTF) whose Tiers range from 0-5 to reflect differing levels of energy access based on capacity, duration, reliability, quality, affordability, legality, health, and safety, and consumption. Tier 4 corresponds to the IEA's definition of access to electricity (1,250 kWh annually) [12, 17]; However, solar lanterns only enable Tier 0 and SHS generally only reach Tier 1 or 2[4] [17].

Prior research has documented the technical, social, and economic aspects of SHS for the interim level of access provided. Technical evaluations of SHS have found challenges regarding quality [18, 19], installation and maintenance [20], and monitoring [21]. Other studies found that SHS impacted household energy spending, the time and quality of children's education, and improved rural livelihoods [20, 22]. However, SHS largely remain out of reach for low-income households [23–25] and affect women and men differently based on time spent in the home [26, 27].

Despite its documented limitations, off-grid solar is still the preferred technology in some rural areas [25, 28]. There is a recent focus on productive uses of solar and payment schemes to support the market's continued expansion. Therefore, this case study examines productive uses and payment schemes as two key pathways through which gender and class can mediate the distributional benefits of off-grid solar.

Productive uses

The United Nations defines a productive use in these contexts as the "creat[ion] [of] goods and services either directly or indirectly for the production of income or value" [29]. While the academic community has long cited the need for consumers to use off-grid energy for productive uses to increase the financial viability of these systems [30, 31], the sector has largely ignored productive uses within the home. ESMAP claims that "increasing productive uses of mini-grid electricity creates a win-win-win-win scenario for mini-grid developers, rural entrepreneurs, communities, and national utilities over time," [30](pg. 17). However, it is unclear if all individuals within the household receive the same level of benefit [32, 33], and studies rarely disaggregate their analysis by gender. Focusing on income generation without explicitly focusing on gender, may unwittingly perpetuate gender inequalities. It remains to be seen if (and how) women are benefiting equitably.

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[4] GOGLA defines SHS as having more than 11 Watts (Wp) solar (Tier 1 access). Systems below 3 Wp are considered lanterns (Tier 0 access) and those 3-11 Wp are considered multi-light systems [16]

Payment schemes

Many off-grid solar companies in East Africa offer their systems to households on payment schemes to lessen the barrier of large upfront costs [34]. Various models exist within the umbrella category of payment schemes, primarily differentiated across two dimensions. First, in terms of long-term system ownership. Lease-to-own models transfer ownership to the household upon payment completion. While, energy-as-a-service models allow companies to retain system ownership and sell only the energy generated [34]. Second, models can deploy payment schemes in terms of different units purchased, namely kWhs of energy or hours of time. For the purposes of this chapter, payment schemes are defined generally as small payments made over time as opposed to a single upfront cost.

The common pay-as-you-go (PAYG) financing model is used for both lease-to-own and energy-as-a service models [34]. PAYG offers more flexible payment amounts and timelines often enabled by mobile money. Although Suri and Jack found that mobile money disproportionately benefited women [35], it is not clear that mobile money combined with a SHS does as well [36](pg.1).

4.3 Conceptualizing and operationalizing energy justice

Energy justice is a body of academic scholarship concerned with the achievement of equity in both social and economic participation in energy systems, while also remediating social, economic, and health burdens on marginalized communities [37]. Prior theorization has organized the concept into three core tenets: distributional, procedural, and recognition justice [38]. Distributional energy justice evaluates the allocation of the benefits and burdens of energy. Procedural energy justice is the equitable engagement of all stakeholders in decision making, and requires "participation, impartiality and full information disclosure" [38](pg.2). And finally, recognition energy justice calls for the fair representation and the offering of complete and equal political rights to all individuals [38]. This chapter focuses on distributional and recognition energy justice in alignment with Sovacool et al.'s observation that energy poverty is a clear violation distributional justice [39] and women (and children's) daily energy supply is often ignored. However, all three tenets require additional research [40].

According to Sovacool, "Distributive justice deals with three aspects: what goods, such as wealth, power, respect, food or clothing, are to be distributed? Between what entities are they to be distributed (for example, living or future generations, members of a political community or all humankind)? And what is the proper mode of distribution — is it based on need, merit, utility, entitlement, property rights or something else?" [39]. This chapter evaluates what goods from solar are distributed and between what entities. In a novel theoretical contribution to the energy justice literature, this chapter operationalizes the concept of energy justice using two modes of distribution inspired by two of the most influential political philosophers of the 20th century, John Rawls and Amartya Sen. Defining:

1. **A primary goods approach** in which every individual has a minimum level of said good, inspired by John Rawls egalitarian perspective in 'A Theory of Justice' [41]. This is to say to each in equal parts – referred to as equal.
2. **A capabilities approach** in which every individual receives according to the level needed to enable the individual to achieve equivalent capability, inspired by Amartya Sen's 'Equality of what?' [42, 43]. This is to say to each according to need – referred to as equitable.

As an example, while an approach prioritizing equality may value equal access to, usage, and impact of off-grid solar, an equity approach would account for the disproportionate burden felt by electricity's absence. Women and low-income households are most impacted by energy poverty, and therefore stand to gain the most from access. Equal and equitable both stand distinct from a utilitarian approach which is prone to reproducing existing gender and class-based social power asymmetries [41].

This chapter builds from prior literature that has discussed capabilities approaches to energy poverty such as Day et al. (2016) [44]. However the application of capabilities vs primary goods approaches to drawing a distinction between equality and equity here is novel.

In addition to the three tenets, energy justice has been defined by eight core principles: availability, affordability, due process, transparency and accountability, sustainability, intra- and inter-generational equity, and responsibility [39, 45, 46]. This research focus on three of these principles: availability, affordability, and intragenerational equity. Availability is access to high quality energy resources, which in this case could be high quality solar home systems; affordability demands that access to these energy resources is not a large financial burden; finally, intragenerational equity is the ability for all individuals to access the available and affordable energy services, which, in this case, may be women or lower income groups not having the same level of access to solar home systems [39].

4.4 Energy justice through energy access

Energy access, and its corollary energy poverty, are inherently issues of energy (in)justice. Critical research regarding both grid and off-grid electricity in Africa has grappled with the implications of post-paid and pre-paid meters [47], heterogenous infrastructure which creates bricoleurs out of desperation [48], and even SDG7, arguing that the goal marginalizes 'traditional' energy sources [49].

Focusing on off-grid solar, there is a growing body of literature questioning whether the market is truly attempting to include low-income households and act as a social and economic good [15]. This emerging research finds inequities in affordability particularly for low-income households [33], and unequal engagement, transparency, and distributed benefits for all stakeholders [50]. Studies have critiqued off-grid solar for adding additional financial burden and expectations onto low-income households [25, 51, 52], and have questioned whether it alone can transform low-income lives [53, 54].

Other literature has revealed that solar companies, in focusing on financing hardware and entrepreneurship, have failed to meet the needs of their low-income customers even with microfinance [33, 55–57] leading to the exploitation and ultimate exclusion of rural, low-income households [15, 51].

In comparison to affordability, intragenerational energy justice of off-grid solar's impact regarding gender is seldom investigated. The studies that do exist have evaluated the impact of solar on gender empowerment in Peru and Bangladesh and found that women with solar spent less time on agricultural activities, more time awake, less time collecting firewood, more time reading, and more time on other chores [58–60]. Overall, discussions regarding the potential benefits of electricity access to women [61, 62] are far more common than studies evaluating whether they occur and to whom they accrue. The call for further research and delivered outcomes on the gendered implications of solar technology is clear [10, 63].

Notably, there is no substantial literature on the intersection of gender and solar energy enterprises or income generation [32]. Only one evaluation of rural solar micro-enterprises in Tanzania differentiated their findings by gender. They found that most businesses were owned by men, and men-owned businesses consumed more electricity than their female-owned counterparts [32].

In the public sector, Tanzania's 2015 National Energy Policy and Rural Electrification Agency (REA) specify a gender action plan. The private sector has female focused solar companies such as Solar Sister and the Tanzania Gender and Sustainability Energy Network [64].

Despite this emerging literature alongside public and private sector initiatives, there are still many unanswered questions surrounding energy justice implications of off-grid solar in Tanzania regarding gender and low-income households.

4.5 Methods: Case study

This case study draws from 187 household energy surveys, 30 in-depth household interviews, 10 follow-up interviews, key-stakeholder interviews, participant observation, and personal experiences in Shirati, Tanzania conducted through multiple fieldwork experiences between 2017-2021.

The first fieldwork in 2017 conducted a household energy survey with 187 households within four villages in Shirati, Tanzania to understand the energy landscape within the villages. Respondent households were chosen through random sampling of every fourth house throughout each village. The baseline survey included questions on the national grid, solar (for lighting and cooking), kerosene, and other fuels. Rather than collecting direct income information, the survey incorporated the Progress out of Poverty Index (PPI) to gauge the socio-economic status and class of households surveyed. The PPI is a ten question survey customized for each country to gauge relative poverty on a scale of 0-100, which will indicate the likelihood of being under specific poverty lines [65]. The index is constructed using indicators such as household size, building materials, and the presence of appliances, tables, animals, and crops. Key informants were interviewed (i.e., solar vendors, medical directors, school headmasters, REA Representatives, mechanics) regarding their solar use throughout the villages.

Following a constant comparison method under a grounded theory approach, data was concurrently collected and analyzed [66]. The baseline surveys and interviews inspired further questions regarding primary sources, productive uses, and payment systems. Additional fieldwork was conducted throughout June-August of 2018 and 2019. To further unpack arising questions surrounding solar, the authors decided to conduct additional qualitative fieldwork over the summer and fall of 2021. This chapter focuses explicitly on the role of gender and off-grid solar uptake by conducting interviews resulting in 30 semi-structured and 8 follow-up interviews with female respondents from both female- and male-headed households. The authors decided to combine the initial quantitative work with qualitative methods to answer not just whether or if gender and socio-economic status interacted with solar energy use, but also how and why. Throughout all the fieldwork from 2017-2021, the first author conduced participant observation of shops selling solar, shops using solar for productive uses, solar technicians, and households utilizing solar throughout their day-to-day life. These points of observation were selected to evaluate human, social, and potentially gendered behavior surrounding solar home systems.

Interview respondents were selected through the snowball method; however, as the interviews progressed, the first author and her research assistant selected identified respondents to be representative of socio-economic status, tribe, and religion in each village based on local knowledge and observation. Socio-economic status was initially gauged by building materials (roof, walls, and floor), compound size, and any visible appliances (motorbikes, panels, satellite dishes, etc.). Later, the interviews included reported monthly income.

The first author and her experienced translator conducted all surveys for quality assurance. The same experienced research assistant conducted all in-person interviews as the first author was unable to travel due to COVID-19 restrictions; however, the first author and her research assistant conducted all follow-up interviews. All surveys in 2017 (pre-COVID19) were conducted either within or outside of participant's homes. The first author and research assistant attempted to always interview the respondents when they were alone. All interviews were conducted outside the participant's home with social distancing and masking recommended. The field team and first author transcribed, translated, and annotated the interviews within the immediately following weeks.

The first author and her research assistant collected all data as described above; the first author coded interviews for emergent themes, which were then grouped into code families [66]. She consulted with her research assistant on these themes. Second, Gill-Wiehl reanalyzed all interviews to ensure replicability and the quality of the work. She wrote the results and discussion in collaboration with her research assistant who solely collected the interview data, as well as the last two authors. Finally, Gill-Wiehl analyzed the data a final time in Dedoose, a qualitative data analysis software, for code co-occurrence and frequency. All authors and the research assistant were engaged in interpreting the data. The key stakeholder interviews, participant observation, and personal experience are not included in the formal analysis, but inform the surveys, interviews, and discussion.

4.6 Results

Study area and socio-demographic characteristics

The case study was conducted in Shirati, Tanzania, in Rorya District, Mara Region, Tanzania (see Figure 4.1). Shirati is a rural town of roughly 50,000 people situated two miles from Lake Victoria and ten miles from the Kenyan border. Shirati experiences distinct dry and rainy seasons (light rains from October-December and heavy rains from March-June) with a tropical climate. Surveys focused on four villages within Shirati, namely Kabwana (n=43), Michire (n=39), Nyamagongo (n=40), and Obwere (n=44), but additional surveys (n=21) were collected from other, farther villages within Shirati. Table 4.1 summarizes selected survey respondent characteristics by village. The average household size was 6.3 individuals, while the average respondent was 39 years old. The survey targeted main cooks as primary respondents as they are typically female in Tanzania and are the most knowledgeable regarding the household's energy consumption; cooking requires most of a household's survival energy needs. However, there are limitations deriving from collecting household level information from individual female respondents. Eighty percent of main cooks (primary respondents) were female. Most respondents interviewed were married, had only completed primary education, and obtained some income from agriculture or business. However, most households pursued farming as a supplemental income source in addition to their primary occupation. The average PPI was 50, which implies that the average household in the study has a 72.2 % likelihood to live on less than 4 USD per day.

Obwere has the largest trading center in Shirati. Women from surrounding villages flock to Obwere on Mondays for market day to buy food, clothing, and other goods. The main road to the market is hugged by electricity grid lines and lined by rows of small shops. At nine shops, customers can purchase solar panels and solar lanterns. Solar lanterns can also be found at most shops selling drinks, bread, soap, and other items. The solar shops sell both branded and generic solar products; however, the most trusted brand in Shirati is Sundar. Solar vendors order their products from Mwanza or Dar es Salaam (the two largest cities in Tanzania) or go to retrieve the products themselves. Forty-five percent of households rely on the market for most of their income. Obwere households are slightly wealthier ($PPI_{avg} = 53$).

Kabwana village has a smaller trading center with roughly fifteen shops ranging from salons, pharmacies, vegetable stands, to multi-purpose shops selling household necessities. The grid lines run alongside the main road. Thirty-three percent of households there rely on the trading post for their income. Kabwana had a slightly higher percentage of female-headed households (40 %) and is slightly wealthier ($PPI_{avg} = 57$).

Nyamagongo is just north of Kubwana. Construction of the electricity grid is proceeding slowly along the main road. Thirty-five percent of respondents farmed for most of their income. Nyamagongo had a slightly higher percentage of respondents attending university (12 %), but a lower percentage of female-headed households (25 %), and the lowest average PPI (43).

Michire is a fishing village on the shores of Lake Victoria. There is one trading post with small shacks selling vegetables, soda, paraffin, and other small supplies. Most households rely on farming and fishing for their income. The REA is working in conjunction with TANESCO to reach houses in Michire along the main road. Thirty-eight percent of households were farmers. Michire had the highest rate of marriage (72 %), the lowest percentage of female-headed households (21 %), and a lower average PPI (48).

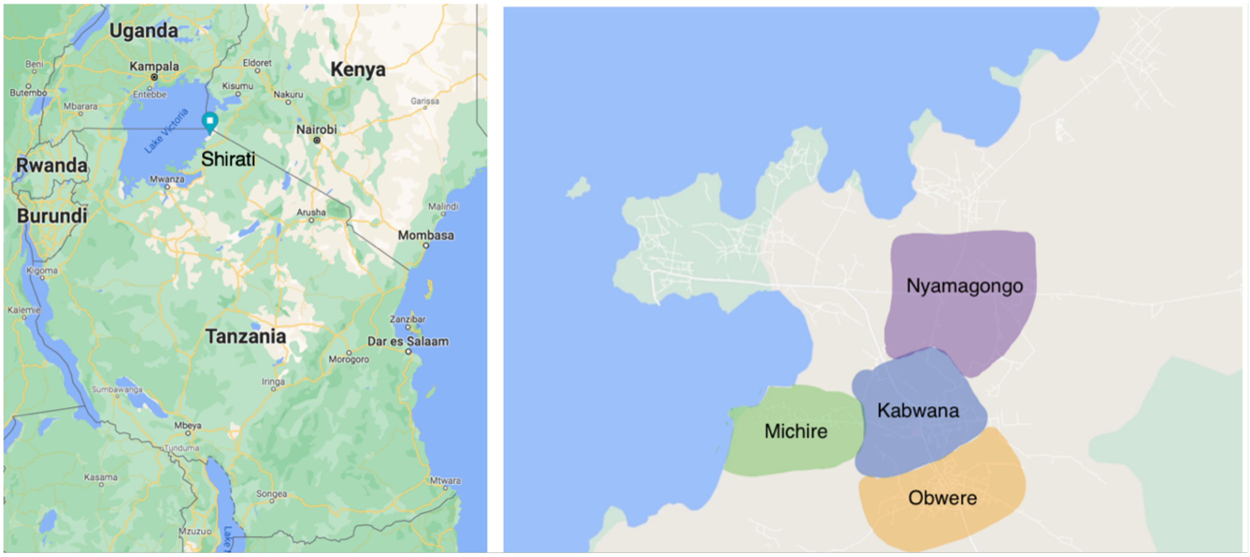

Figure 4.1: Left: Shirati within the country of Tanzania. Right: The villages of Michire, Kabwana, Nyamagongo, and Obwere within Shirati.

Solar and grid use

Table 4.2 describes solar, solar lanterns, and grid prevalence among respondents. Twenty-two percent of households were connected to TANESCO (the grid). The grid tariff operates on a prepaid system and customers paid 11,700 TSH (5 USD) monthly through their mobile phones, 50 cents USD (1,000 TSH) at a time. No household used electricity for cooking.

Although 97 % of households want to connect to TANESCO, there is a lack of knowledge of what it costs, how construction proceeds, and how initiate the process. The monthly grid tariff is not perceived as expensive, but the upfront cost of connection is considered prohibitive. Overall, the surveys revealed that women value electricity primarily for lighting, followed by radio and television, with cooking last. Women additionally praised solar for the lack of smoke when it replaced kerosene.

Of the payment schemes available for off-grid solar, the lease-to-own model was the most common throughout the villages with relatively short payment terms of 5-6 months. However, families often perceived these payment plans to be unjust. Women often asked, “[if]

	Overall (N=187)	**Kabwana** (n=43)	**Michire** (n=39)	**Nyamagongo** (n=40)	**Obwere** (n=44)	**Other** (n=21)
Household Size (Individuals) Mean (s.d.)	6.3 (3.6)	5.9 (2.6)	5.8 (3.5)	6.5 (3.2)	6.6 (4.8)	7.2 (3.2)
Age (Years) Mean (s.d.)	39 (16)	37 (16)	40 (18)	41 (16)	38 (16)	42 (13)
Female-headed Household (%)	30%	40%	21%	25%	27%	38%
Female Main Cook (%)	80%	91%	64%	73%	82%	90%
Occupation (%)						
Cares for Home, Children	17%	21%	26%	15%	16%	0%
Farmer	31%	23%	38%	35%	14%	62%
Business	31%	33%	21%	28%	45%	24%
Other	21%	23%	15%	22%	25%	14%
Marital Status (%)						
Single	12%	23%	8%	10%	11%	4%
Married	65%	54%	72%	68%	68%	64%
Divorced	1%	0%	2%	0%	2%	0%
Widow	20%	21%	18%	15%	18%	33%
Education Level (%)						
No Education	10%	15%	15%	5%	5%	5%
Primary School	62%	51%	62%	63%	61%	86%
Secondary School	21%	28%	15%	20%	27%	5%
University	7%	6%	8%	12%	8%	4%
Progress Out of Poverty Index Mean (s.d.)	50 (13)	57 (12)	48 (13)	43 (13)	53 (13)	45 (12)

Table 4.1: Household demographic information from surveys. All percentages and indices are rounded to whole numbers leading the sum to differ from 100%

	Overall (N=187)	**Kabwana** (n=43)	**Michire** (n=39)	**Nyamagongo** (n=40)	**Obwere** (n=44)	**Other** (n=21)
Only a solar panel	9%	0%	3%	35%	0%	5%
Only a solar lantern	36%	42%	36%	30%	32%	32%
Both solar panel and lantern	8%	7%	10%	13%	2%	10%
TANESCO (grid)	22%	44%	15%	5%	32%	0%
TANESCO and solar	7%	16%	0%	5%	7%	5%
Given that household has a solar panel or solar lantern						
Solar is used for Lighting	100%	100%	100%	100%	100%	100%
Phone charging	21%	4%	15%	32%	30%	25%
Radio	17%	4%	12%	20%	26%	25%
TV	17%	4%	12%	20%	19%	42%
Paid for on Payment Scheme	18%	40%	7%	27%	25%	0%

Table 4.2: Solar, solar lantern, and grid use from surveys in 2017

the energy is free, why do we keep having to pay every month?" This perception of injustice may explain the lower-than-expected prevalence of payment schemes (18 %). Solar companies that offered payment schemes were generally disliked by the community. Respondents viewed the payment agreements as expensive after comparing the total cost of the payment plan to the one-time cost of a panel. Therefore, the qualitative interviews further expanded upon why these payment plans, designed to aid affordability for low-income households, were perceived as less just.

Surveyed solar systems ranged from 5-250 Watts. The average system in the 187 surveys was 68 Watts, but 60 Watts in the 30 in-depth interviews[5]. Of surveyed households, 9 % had only a solar panel, 36 % had only a solar lantern, 8 % had both a panel and lantern, and 22 % had only TANESCO.

This chapter investigated the relationship between solar, solar lanterns, PPI, and head of household gender using ordinary least squares regression while controlling for education, religion, and other socio-demographic characteristics. Neither PPI nor having a female-

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[5] However, most interview respondents did not know the size of their system extempore; therefore, these numbers reflect only the system sizes known by respondents.

headed household was correlated with the presence of or size of a solar panel or lantern. Solar and solar lantern use dis-aggregated by phone charging, radio, or tv was not statistically affected by gender or PPI. This lack of a statistically significant relationship evidences that while solar panels and lanterns are not disproportionately absent from the lives of low-income or female-headed households, they are not disproportionately present in it either. These findings simultaneously challenge a study from rural Ethiopia that found that female-headed households were more likely to adopt solar [67], and a study from Senegal found that single, divorced, or widowed women were less likely to adopt solar [27]. The results suggest relative equality in the adoption of off-grid solar across female-headed and low-income households; however, these results do not imply equity. Women may have equal access to men; however, given existing socio-cultural disparities and exclusion, off-grid solar must strive towards equity rather than equality.

Given this landscape, this section now turns to the 30 in-depth interviews conducted with women specifically regarding solar as their primary source of energy, as a source of income, and as a financial burden on their household. Thirty female respondents were selected from households that already had solar systems and were representative of socio-economic status, tribe, and religion in each village based on local knowledge. Households with only a solar lantern were excluded as lanterns constitutes only Tier 0 of ESMAP's MTF [17] and do not meet IEA's definition of electricity access [12]. SHS typically do not reach the IEA's definition of electricity access (ESMAP's MTF Tier 4); however, no household obtained Tier 4 level electricity access through solar energy. Thus, to study solar in Shirati, Tier 2 and 3 access were included as well. The interview criteria ruled out households without access to solar panels, therefore, the results may not include the lowest income percentiles. Only four of these 30 households were female-headed, reflecting either Shirati's traditionally patriarchal structure, or that female-headed households cannot afford solar systems. Twenty-one women reported inconsistent income sources. When asked about her income, one woman responded, "we have no consistent income, we just work and expect to get what is enough for a day." The average annual household expenditure was 1140 USD, slightly higher than the country's GDP per capita (1090 USD).

Low-quality products

Respondents complained even before the interviews began about solar product quality. Multiple respondents had broken components, and others complained that quality rapidly decreased over time, explaining that they use solar "for lights, no longer to charge the phones as the battery is not good." Another lamented that "the solar is not as good as it used to be in the only two years since we bought it. But now, we cannot watch our television." Respondents were often required to purchase a new battery every year. Poor quality even led one respondent to say, "I think we had a fake one because as the days goes on it is reducing its functioning."

One of the largest solar shopkeepers in Shirati explained that higher quality products were available in Mwanza and Dar es Salaam, but he didn't stock them because "the people of Shirati are not used to very expensive products.” This research was unable to track the ratio of generic to branded products; however, shopkeepers noted that customers preferred the generic lanterns that were 5,000 TSH (2 USD) cheaper.

The predominance of low-quality products in Shirati can be explained both by the paucity of wealthy families in Shirati, and its remote, rural location. Solar vendors complained of the additional transport costs of higher quality products, given the perception that they would not sell. Therefore, as found in Kenya [67] and Malawi [68], residents of Shirati do not receive equal or equitable access to high quality solar products.

Primary use

Although SHS are intended to provide primary energy access to formerly unelectrified populations, households across Africa often rely on SHS as secondary, back-up, electricity sources in the face of unreliable grids [69, 70]. In this configuration, homes have “stacked” systems in which the grid and SHS run parallel circuits throughout the home, using one when the other fails. In general, wealthier households are more likely to use solar this way, seemingly taking a step down the traditional energy ladder as found in Rwanda [71].

The semi-structured interviews therefore investigated whether solar systems were mostly used as primary or secondary electricity sources. Roughly half of the households interviewed used solar only as a back-up during the frequent grid outages - a striking increase over the 2017 results (Table 4.2). This may reflect that households who could originally afford solar obtained electricity in the interim 4 years. When solar was the primary electricity source, households prioritized lighting, phone charging, and watching television, but rarely ironing. Households felt they could not rely solely on solar either, particularly during the rainy season. Solar also could not run larger electric appliances. These results confirm previous literature [15].

Households using solar as their primary electricity source had lower average annual expenditure (948 USD) than households using solar as a back-up (1560 USD). This suggests that solar is within reach of households hovering around the national GDP/capita but plays an equally prominent role as a back-up source for wealthy rural households. The survey results show that solar lanterns reach even low-income households, but as previously mentioned, a single lantern does not constitute any tier of energy access. Primary solar users paid on average 55 % of their monthly income for their system, compared to secondary users who paid 74 %. This suggests that secondary solar systems were larger or more extensive. High- and low-income households may have equal access to solar, but the difference in primary and secondary use leads to inequitable access to electricity.

All female-headed households in the in-depth interviews used solar as a secondary source of energy. The sample size for female-headed households was very small, which could suggest that solar is not accessible to female-headed households. None of the major solar reporting agencies or databases record whether solar is a primary or secondary source. Overall, this research attempts to contribute to the insufficient literature regarding whether gender affects household use of solar as a primary or secondary source.

Equal benefit

There was a common perception of equality regarding the solar system as shown in Figure 4.2. When asked how different family members benefited from solar, a respondent utilizing solar for light, charging, and tv explained that "no one benefits the least because we all have the same kind of use," while another woman said, "I don't think I benefit more from solar than other members of my household because we are all using solar for the same reason." Households equated equality in access and benefit with the number of uses. A woman who used solar for lighting, television, and phone charging, explained "my husband benefits the least because he normally leaves very early in the morning and returns late at night, so he does not watch TV and rarely charges his phone at home." However, another said, "I think my husband benefits more than me because he watches television a lot more than any other person" and explained that her son benefited the least "because he only uses solar to charge his phone though not regularly." Other respondents described that "the ones who benefit the least are the children because they do not have phones to charge." The respondents who reported inequality reflected on the amount of time each household member utilized each use of solar, while those who reported equality reflected only on each member's number of uses. Previous studies that labeled household spaces and tracked the presence and use of electric appliances found inequity in access [72]. Although women reported benefiting equally from the solar system, no household reported having solar-powered lighting within the kitchen area, which has also been found in Kenya [73]. All households, even those with electricity and solar back-up, continued to have the typically female cooks hold a phone in their mouth as a flashlight while cooking the family dinner.

Claiming to know about the solar system was a ubiquitous theme, but respondents also asked to know more. Female respondents would often go to ask their husbands how much the system cost before returning to the interview. This ambiguous result seemingly conflicts with the survey that recorded confusion surrounding the payment schemes. Previous literature confirms information injustices regarding solar energy [74]. The surveys and in-depth interviews were conducted in 2017 and 2021 respectively, signaling that the increased diffusion of solar information in Shirati has not been sufficient to achieve full knowledge and confidence regarding the systems, particularly for women.

Solar is productive, but rarely generates income

Respondents stressed the value derived from solar, regardless of whether it was a source of income, commenting that their households greatly appreciated the opportunities for lighting and phone charging (Figure 4.2). A primary user explained that "we benefit from solar since we do not stay in the dark at all… It's better than not having anything at all." A secondary user noted, "with solar I can still have some activities done as usual [when the electricity is out] ... so with solar I benefit even if not monetarily." Another secondary solar user said "With Shirati, electricity tends to be a little bit disturbed sometimes. With solar, we are sure of getting all the services we need." A final secondary user commented on their children by saying, "the kids are not bored since they can still watch television as usual when the electricity goes off."

Only 3 of the 30 households interviewed used solar for income generating purposes (Figure 4.2). These purposes included a barber shop and phone charging station, a small theatre, and a household only charging phones. All three respondents reported using the money obtained from these enterprises to purchase food and school fees for their children; however, none of these households were female-headed.

A respondent's husband opened the barber shop in 2019 with only solar but connected to the national grid in 2020. The shop uses both solar and the grid because the respondent's spouse is afraid that the solar battery will die if left unused. Therefore, the shop uses the grid to boil water and to power a fan, tv, and speaker, while solar powers the haircutting and styling tools. The solar system is too small to boil water or power the larger appliances, but both solar and the grid provide lighting. The shop typically has 10 customers daily (both men and women) and charges 1,000 TSH (0.5 USD) per cut. The respondent explained "through solar he is sure to work throughout the day and may continue providing service to customers in case there is no electricity ... it's the work we depend on." The respondent's husband hired another male barber but claimed to be unable to hire a woman as they must be hired at female saloons.

Another respondent's spouse ran a theatre for movies and soccer games using a projector and a sheet in their living room. The theatre runs films 1-2 nights weekly, charging 500 TSH (0.25 USD) per ticket. Roughly 10-20 people attend each viewing depending on the movie. During soccer games, 50-60 individuals huddle to watch.

The third respondent charges phones for a small fee; 200 TSH (0.115 USD) for non-smart phones and up to 400 TSH (0.25 USD) for smart phones. However, the respondent explained that she had customers primarily when the grid was out.

Some respondents, particularly those using solar only for light or those from low-income households, charged their phones or batteries (if their panel was broken) on a neighbor's solar or grid-electricity for free. A respondent explained that "[the female neighbor] is just giving me help." This revealed that some households had the opportunity to generate income from their solar but chose otherwise to help their neighbors. Charging neighbors' phones may not have generated income but did build social capital demonstrating non-monetary priorities.

Upfront cost vs the burden of frequent payments

Previous literature has documented that the low, irregular, and inconsistent incomes of the poor [75] plague households with constant worries about recurring bills [76]. Most interview respondents (26/30) reported purchasing their solar with a one-time payment, rather than a payment plan noting that a one-time payment for solar did not pose a financial burden (Figure 4.2). A woman explained that "we only paid for the solar once, so we had no financial burden." Another respondent explained that "paying little-by-little [through a payment plan] seems like a burden to us. I fear that I may not get the money." This fear of debt or inability to make payments is reinforced by literature on shameful experiences of solar repossession [15].

Generally, respondents did not have favorable views of payment plans, although these perceptions were not from personal experience. A respondent, having heard about payment plans from a neighbor, said it was very expensive, requiring 2,000 TSH every two days for an entire year. A respondent's husband, who joined an interview to provide further details on their productive use of solar in the barber shop, acknowledged that he'd rather pay for a less expensive solar, even if it was a one-time cost. A respondent who purchased solar on a lease-to-own model paid 40,000 TSH monthly for three months. However, they did not view it as a financial burden as they now owned the product, noting "we did not pay for it for so long." The four households who chose a payment scheme to purchase their solar now own their system. The perceived financial burden was not associated with the total amount of the payment plan, but rather its length.

The low rate of payment plans may be attributed to feelings of injustice. Low-income households cannot afford SHS even with financial payment plans while households purchasing SHS can afford the systems without a plan. Another possibility is that households dislike frequent or lengthy payments, even if individual payments are smaller. Finally, it appears that local solar vendors offered an alternative to contractual agreements with foreign solar companies.

The interviews revealed a unique arrangement in which some households brought money to shopkeepers little-by-little until they reached the full amount for the system. A shopkeeper explained that when a customer pays any amount, he provides a receipt. Once the full amount is paid, the customer can pick up their solar. In this arrangement, the customer does not have to sign an agreement with a foreign solar company and can take as much time as needed. Households considered this arrangement as saving for a one-time payment through the shop rather than a form of payment plan.

Respondents preferred a one-time payment or paying at the shop little-by-little because "I might not have the money when I need it according to the agreement, so I would rather stay with the less expensive one that I can pay one-time." Additionally, households explained how they benefited from solar because after that one-time payment "there are no charges." Households appreciated the freedom from continuing bills, possibly explaining the low frequency of energy-as-a-service models for SHS across East Africa. Others noted benefiting from solar because they do not "pay any bills for solar." One woman explained, "I usually get money once, so by the time I get money I just want to buy everything that is required, so when I got the money, I could not think of anything else, I just went to buy the solar." This reveals the difficulty households face in smoothing irregular incomes, which small recurring payments require.

Other households saved up for their solar at home through a lockbox. One woman explained that she used to save for her solar at home because "the family was not that big, I could manage [the money]"; however, she now brings the shopkeepers money little-by-little because her family is larger, and if the money is at home it may be used for something else.

This is an interesting finding as payment schedules are often touted as a way to alleviate the financial burdens of the poor. In theory, financial schemes break down high upfront costs into small payments, easing liquidity constraints [75]. The results from this case study, however, seem to suggest that the frequent of small payments adds an additional burden onto low-income households. With a one-time payment for solar, households are freed from this seemingly endless financial struggle at least for one need. Even households who save through shopkeepers are freed from burdensome contractual agreements.

Some energy justice literature suggests that financial schemes are a path to increase accessibility of solar to low-income households [33, 77, 78]. While other literature questions how affordable PAYG technology actually is for low-income households [25, 51], even with partitioned upfront costs [79] and theoretically low interest rates[6].

Payment plans may increase access in some instances, but this increased access should be balanced against an acknowledgment of parallel injustices regarding the psychological burden of frequent, regular payments. Low-income households may not have 50-70 % of their monthly expenditure readily available to spend. Therefore, payment schemes can alleviate the inequity of access but may increase inequity in the overall burden of financing access.

Solar home systems are not reaching low-income households

This ethnographic work revealed that low-income households can only afford solar lanterns, not systems. Additionally, the surveys revealed that within Shirati, a relatively low-income community, only owning a solar lantern was twice as prevalent as owning a solar panel (36 % vs. 17 %) (Table 4.2). Therefore, off-grid solar perpetuates the energy access gap across class.

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[6] In practice, interest rates on payment schemes for SHS are nontrivial.

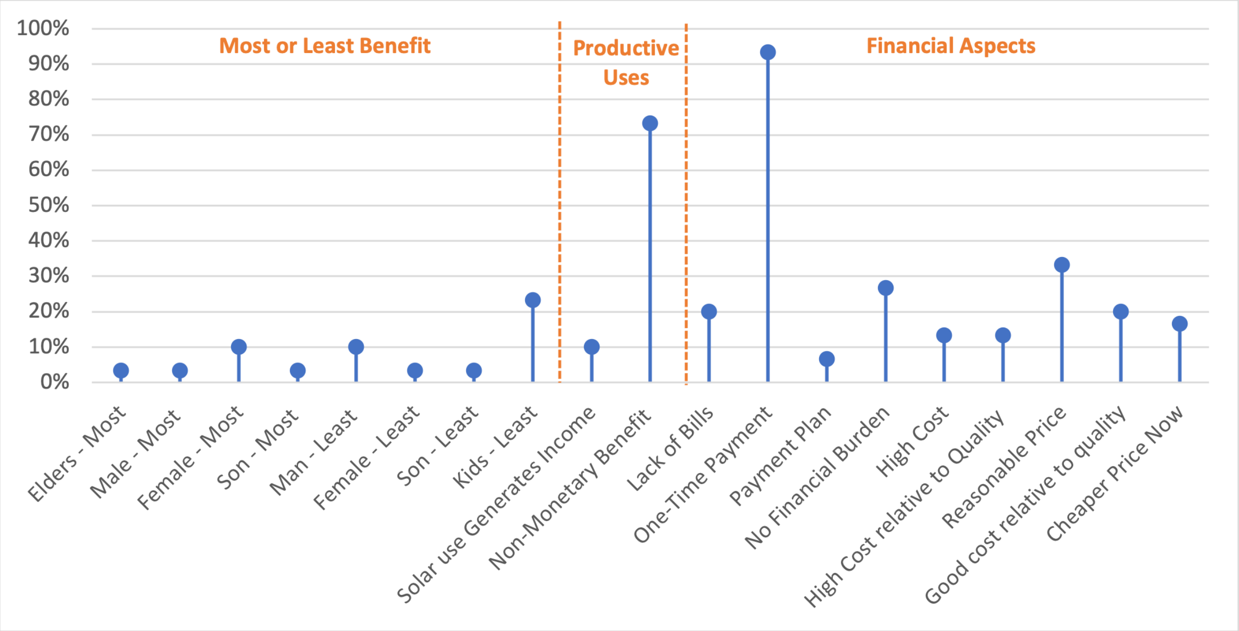

Figure 4.2: Frequency of selected codes in qualitative interviews from 2021. Themes are ordered into groups regarding: i) who the respondents felt benefited the most or least if the distribution was not equal, ii) how the solar was used productively (income and non-monetary benefits), and iii) how the system was financed.

4.7 Discussion

This case study reveals mixed results surrounding gender's mediating effect on solar use. Although solar does not seem to actively disadvantage women, solar's deployment is not a clear win for gender equality as was previously promised. Achieving equity from a capabilities approach would call for solar's benefits to be distributed equitably according to individual circumstances, while a primary goods' approach would lead to everyone obtaining equal levels of electricity access. This case study reveals that solar may achieve equality under a primary good's approach, but primary goods do not map to the same capability for every person [42, 43]. This is particularly salient in terms of gender as revealed by the in-depth interviews. Respondents that perceived an equal distribution were primarily evaluating shares using a primary goods approach (how many uses), while those who recognized a difference in access focused on the time utilizing each service and the capability achieved from that use. Fundamentally, SDG7 takes a primary goods approach in wanting to achieve a certain tier or basic bundle of electricity for all. However, in pursuing approaches that insufficiently address gender and income, SDG7 ignores existing culturally bound disparities that limit individual capabilities. Energy equality and primary goods approaches are not enough. The global community must actively recognize and prioritize marginalized genders and low-income households within off-grid solar and electricity access.

In terms of the availability principle of energy justice, this research found that high quality solar products were not available in Shirati as the shopkeepers perceived the rural, low-income community as unable to afford these products. Additionally, higher quality products were practically not available to the respondents who preferred a lower quality product over a payment scheme for a higher-quality product. Poor quality products led respondents to limit their electricity uses and appliances, purchase new batteries frequently, or use a neighbor's panel to recharge their own battery. Therefore, there is an availability injustice in the off-grid solar market in Shirati when it fails to provide "sufficient energy resources of high quality" [39](pg. 5).

In this case study, off-grid solar is the primary energy source for most low- and middle-income households and serves as a back-up source for middle- and higher-income households. This is not inherently problematic; reliability and back-up sources are very important given the intermittency of the grid. However, energy access literature or optimization models rarely acknowledge this widespread secondary use of SHS in Sub-Saharan Africa.

At the intersection of the affordability and intra-generational principles of energy justice, this chapter finds that financial payment schemes for solar may be further burdening low-income households with frequent payments. Future research is needed to investigate the psychological effects of financial payments, particularly regarding off-grid solar. These results may only be applicable to the income levels that can currently afford solar. For extremely low-income households, affording energy access may be worth the psychological burden. However, the literature should investigate this trade-off. Overall, the results suggest that off-grid solar is not currently a clear win for women or low-income households.

Finally, there was a lack of income generating uses of solar, but a plethora of non-monetary benefits. Despite increasing interest in income generating uses of solar [30], the results suggest that these modalities have not reached rural, low-income communities, and do not seem to be disproportionately helping women. Therefore, the solar community should prioritize rural, low-income communities and women to own solar for income generation. Women benefit from solar in other non-monetary ways such as lighting, phone charging, and entertainment for their children. The off-grid solar community should focus on the services and value that solar is adding to these households regardless of monetary benefit. Further efforts are needed to quantify the indirect productive uses of solar. These results reveal that off-grid solar has benefits beyond income, but its reach is currently limited.

Gender & income cognizant solar energy policy

Further work in the field is needed to ensure that women and low-income households are included and prioritized in both the distribution of benefits and in the decision-making process. Researchers and policymakers can contribute by taking gender and income-cognizant approaches and differentiating reported impact data by both gender and income.

4.8 Conclusion

The aim of this work was to evaluate how the distributional benefits and burdens of off-grid solar are mediated by gender and class, specifically within a rural setting in Tanzania. This case study does not find clear benefits specifically for women or low-income households, suggesting that off-grid solar usage may be equal, and thus not perpetuating current injustices, but is still not equitable. Off-grid solar users benefit, although not always monetarily.

At the center of this discussion lies a paradox: SHS are promoted to increase the quality of life and economic prospects for women, children, and low-income households, but solar systems beyond lanterns remain out of reach of the low-income households and women and children do not seem to benefit substantially more than men. These findings can be interpreted to mean that current energy policy is not sufficiently addressing the needs of different genders and low-income households, who have a dis-proportionally lower baseline level of energy access. Rural economic and energy policy should consider these differential capabilities to benefit from solar energy, and thus track and prioritize progress for these group explicitly. Theoretically, this study outlines the different implications of evaluating energy access through a basic need versus a capabilities approach and calls for the energy community to prioritize the capabilities approach to energy justice. Although energy access has the potential to enable a wide range of SDGs, for now, the justice gap remains.

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Chapter 5

Measuring the reliability of SDG 7: the reasons, timing, and fairness of outage distribution

Preface

The second application chapter examines the equity of electricity reliability from energy sources providing energy access in Tanzania, Kenya, and India.

The United Nations Agenda for Sustainable Development makes energy access one of its core goals through Goal 7: ‘Ensure access to affordable, reliable, sustainable, and modern energy for all by 2030’ [1]. As efforts towards the goal have progressed, the variety of systems providing access has expanded to a continuum of options from grids to minigrids to solar home systems [2]. However, the focus of efforts has remained at the level of access, not the comprehensive picture explicitly expressed in the goal. In particular, reliability - and the household experience of reliability - are particularly understudied perspectives in energy access and energy justice literature. This chapter fills this gap by empirically studying the reliability of household electricity access in Tanzania, Kenya, and India using data from a diverse set of technologies including solar-home-systems, pico-grids, and national grids. It thereby investigates inequities and trade-offs between the benefit of access to electricity and the burden of unreliability. This chapter uses several methods to compare inequalities in reliability across different systems using several of the methods from Chapter 3, notably Lorenz Curves.

The work in this chapter was previously published in the journal Environmental Research Communications in 2022 as an article titled ”Measuring the reliability of SDG 7: the reasons, timing, and fairness of outage distribution for household electricity access solutions.” It is included in this dissertation with permission of my co-authors Duncan Callaway and Daniel M. Kammen.

Abstract

The United Nations identifies ensuring "access to affordable, reliable, sustainable and modern energy for all" as one of its Sustainable Development Goals for 2030. This chapter focuses on the comparatively under-investigated question of reliability within the broader goal. This chapter empirically studies experienced household electricity reliability using common frameworks in key countries such as Tanzania, Kenya, and India. Datasets represent a diverse set of technologies including solar home systems (SHS), solar pico-grids, and national electricity grids. First, the prevailing reliability metrics - SAIDI and SAIFI – are measured for all datasets. Informed by critical assessments, this chapter then proposes a suite of new metrics that facilitate improved reliability comparisons by considering the reasons, timing, and fairness of outage distribution. Analyses using the proposed metrics reveal key policy implications for addressing energy poverty in the Global South. Acknowledging that the systems studied provide different capacity, affordability, and carbon footprints, on average, SHS provided comparable hours of lighting to local grid connections, however SHS outages were less equally distributed than those from other sources. In addition, calculations of grid reliability were highly sensitive to measurement techniques and assumptions used, necessitating high resolution data for policy decisions. Finally, economically driven outages conspicuous in pre-paid SHS systems (i.e., disconnections for non-payment) composed a significant portion of experienced unreliability. These findings quantify the important contribution of demand-side affordability to experienced household reliability, thereby allowing for a comprehensive understanding of the reliability of SDG 7.

5.1 Introduction

Access to modern energy services underpins progress in all areas of development including economic growth, education, public safety, gender equity, and access to water and health services [3, 4]. Therefore, the United Nations (UN) included a goal of ensuring "access to affordable, reliable, sustainable, and modern energy[1] for all" in its 2030 Agenda for Sustainable Development, aka SDG 7 [1]. The World Bank (WB) stated that with 11 years left to achieve the goal, 759 million people lacked electricity access, indicating the magnitude of SDG 7's ambition [5]. 76% of that unelectrified population lived in twenty developing[2] countries in Sub-Saharan Africa (SSA) or South Asia. The COVID-19 crisis has further challenged electrification efforts, even reversing progress in several SSA countries.

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[1] The goal includes access to clean fuels and technologies for cooking; however, this chapter focuses exclusively on electricity access.

[2] Most of these countries are low- or low-middle-income economies in the WB classification (which also refers to them as developing countries). Here, the developing country label does not imply that all economies in the group are experiencing similar levels of development or that other economies have reached a preferred or final stage of development. Rather, this term is adopted for simplicity. See also: Power for All's definition of low-energy-access countries [6](p. 14)

"At today's rate of progress, the world is not on track to achieve SDG 7" [5]. Therefore all electricity access options must be considered.

Alstone et al. presented a framework that conceptualizes the options for gaining electricity access as a continuum of solutions ranging from personal 'nano' grids to solar-home-systems (SHS), to minigrids, to utility-scale systems [2]. The International Energy Agency (IEA) reports that "decentralized solutions are the least-cost way to provide power to more than half of the population gaining access by 2030" [7]. As of December 2018, 108 million people globally were living in a household with improved energy access through decentralized solar systems [8]. Rather than a universally appropriate approach [9], decentralized systems have a substantial role in energy access efforts alongside grid extension, particularly in the short term and in rural areas [10]. In their rise, decentralized systems challenge prior assumptions about energy systems and techniques used to measure them.

Several organizations have since put forward frameworks to define energy access beyond just the number of connections[3]. Starting in 2010, Practical Action's Poor People's Energy Outlook series presents an Energy Access Index that sets minimum standards and distinguishes levels of access in terms of household fuels, electricity, and mechanical power [13]. The most common framework is ESMAP's (The World Bank's Energy Sector Management Assistance Program) Multi-tier Framework (MTF) [14]. It states: "To be meaningful for households, productive enterprises and community facilities, the energy supply supporting that access must have a number of attributes: it must be adequate in quantity, available when needed, of good quality, reliable, convenient, affordable, legal, healthy, and safe." Their 'tiers of access' framework recognizes that not all modes of access are equivalent, partitioning tiers – which rank from 0 (lack of electricity in any meaningful form) to 5 (aspirational goal for access) – based on attribute thresholds.

While reliability is included in the text of both the Sustainable Development Goal and ESMAP's MTF, it is understudied in comparison to wealth of research on energy access overall. Additionally, literature highlights the insufficiency of the prevailing methods for comparing reliability. Several authors have discussed the arbirarity of MTF tier thresholds, applying to only two of the six tiers of access [15–17]. Jacome et al. focuses on the dearth of information about reliability experienced by households [18].

To fill these key knowledge gaps, this research provides an empirical comparison of household electricity reliability across the continuum of energy access solutions. First, the reliability of SHS, solar pico-grids (SPG), and national electricity grids are measured using primary and secondary data from three key energy access countries: Tanzania, Kenya, and India. The prevailing reliability metrics (SAIDI and SAIFI) are critically assessed, inspiring the introduction of a suite of new metrics that examine the reasons, timing, and fairness of outage

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[3] Even the definition of grid 'access' changes with location. E.g., the Rural Electrification Agency (REA) of Kenya, considers households within 600 meters of a transformer as having 'access' regardless of the presence of electrical wiring inside the household. 'Connected' is used to designate what the broader literature implies when using the term 'access' [via personal communication with REA staff in 2018]. In India, an entire village is considered electrified if distribution lines are present, and electricity is provided to public buildings - such as schools and health centres - and only 10[11, 12].

distribution. Analyses using these proposed metrics inform four key policy implications for addressing energy poverty in the Global South:

1. *Studies that evaluate the impacts of unreliability need high temporal and spatial resolution data directly measured on the communities of interest.*
2. *For household electricity access in particular, the existing reliability metrics (SAIDI, SAIFI, Multi-Tier Framework) are insufficient for informing SDG 7 policy decisions.*
3. *The affordability of energy access solutions is already becoming as important as access to the solutions.*
4. *Fairness and inequality must be at the forefront of efforts to improve the service quality of electricity solutions in Sub- Saharan Africa.*

5.2 Context and Gaps

Most energy access literature that references reliability and decentralized systems identifies the opportunities for decentralized renewable energy (DRE) systems to provide improved reliability in the context of non-existent or unreliable centralized power grids at similar or lower costs [6, 19–23]. However, several articles including [22, 24–26] reveal concerns about the level of service and reliability of DRE systems in practice, particularly through narratives of unreliable SHS. Their concerns can be partially attributed to the poor quality of the first products to enter these markets, as well as counterfeit products, [8, 27] but there remains a troubling lack of quantification of the reliability and service quality of DRE writ large.

An absence of transparency, standards, and reporting persists across the off-grid solar sector [13, 26] despite efforts such as Lighting Global's solar product verification program, "resulting in huge discrepancies in reported metrics and mistrust among stakeholders" [28]. "Technical reliability studies are rare … even though service quality analyses would be important to help in capturing the full potential of these systems in the future" [22]. Even for many utility grids in developing countries, there is almost no data on electricity reliability for even the most basic patterns of outages [29] and public information is rarely available [30, 31]. This dearth of data severely limits the fields's ability to measure the reliability of electricity access in efforts to achieve SDG 7.

Prior economics literature evidences the severe negative impacts of electricity unreliability using a diverse set of approaches [32]. Research ranges from the impact on gross-domestic product [33], to businesses and industry [23, 34], household incomes [35], and health [36, 37]. Literature on the willingness to pay for increased reliability, even in financially constrained environments, quantifies the value that households and businesses place on reliability [18, 38–40]. With such large potential impacts on energy poverty, it is vital that reliability is measured and evaluated accordingly.

The prevailing methods of measuring distribution grid reliability, SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Interruption Frequency Index) detailed in Section 5.3, are not without their own critiques. Nateghi et al. (2016) critiques how reliability standards and metrics in the United States insufficiently internalize the impacts and risk of large exogeneous disturbances such as natural disasters [41]. Heylen et al.'s 2019 article critiques the lack of quantifying fairness in the context of power system reliability and proposes both variance-based and Gini-based metrics [42] from which the proposed fairness and inequality metrics in Section 5.4 build. These critiques, however, still fail to evaluate the usefulness of the prevailing methods when applied on energy systems in developing countries, or on decentralized systems. Harish et al. (2014) notes that the prevailing methods have the potential to misrepresent experience unreliability qualitatively, especially at the magnitude common to most developing countries [12]. These metrics need to be more "informed by an understanding of the context and the impacts on populations rather than merely number of hours of outages" [43]. Reliability, as a popular concept, includes many facets and is difficult to quantify and measure especially at the household level [43, 44]. However, it is vital that the metrics used can sufficiently describe household reliability patterns and inequities, particularly for applied research and policy.

Therefore, this research uniquely fills the following literature gaps. While SHS are an increasingly large contributor to global electricity access, there have been no systematic evaluations of measured experienced reliability for households with SHS in Africa prior to this chapter. In fact, there are no empirical comparisons of reliability patterns across electricity access options whether decentralized or centralized [22, 43, 45]. Additionally, the standard reliability metrics designed for advanced power systems face challenges when applied to underdeveloped, unreliable grids and decentralized systems providing electricity access. By documenting and surmounting these challenges with validated, transparent, and systematic methods, this research demonstrates significant advantages over other existing literature on electricity reliability in the global south.

This chapter presents several novel and insightful contributions. First, it quantitatively compares customers' experienced reliability across different technologies using a common framework, including a detailed evaluation of experienced SHS reliability. On average, SHS in the presented data sets provided comparable outage frequencies to their local grids, but the distribution was less equal than for other sources. Second, it shows that the geographic scope, temporal granularity, and level of the electricity grid strongly impact the size and variability of grid reliability measurements. This variation in measured reliability indicates that assessments of the fairness of access require relatively high spatial and temporal resolution. Finally, it proposes new reliability metrics that evaluate three key overlooked factors: outage cause, timing, and the fairness of outage distribution. After categorizing SHS outages by their cause (solar resource availability, failure to pay / economic, or technical failure), each category has strongly different patterns across space and time. This finding indicates that charting a path to improved reliability requires careful consideration of what characteristics of unreliability one wishes to address. For example, economic outages (loss of service due to failure to pay bills) are conspicuous drivers of pay-as-you-go (PAYGo, pre-pay) SHS customers' experienced reliability but are rarely considered in reliability metrics and broader reliability literature. Moreover, due to solar resource availability, SHS outage timing is strongly biased towards early evening relative to other modes of access. This suggests social impacts that fall on household activities such as evening chores and homework, and points toward a focus on improving system sizing rather than technical failure rates to manage reliability impacts for these customers.

The remainder of this chapter is organized as follows; Section 5.3 describes the methods by reviewing and critiquing reliability metrics and introducing the data sources; Section 5.4 analyzes the data using existing reliability indicators and proposes new metrics for evaluation; Section 5.5 details policy implications for addressing energy poverty; Section 5.6 notes limitations and opportunities for future work; and Section 5.7 concludes this chapter.

5.3 Methods

To match this chapter's intentions of investigating the reliability of SDG 7 with the methods available, the term 'experienced household reliability' is defined and advanced. It is a composite concept consisting of supply and demand-side issues that both prevent households from turning on their lights and accessing the benefits of electricity. Rather than assessing bulk system reliability (generation-side on grids), experienced reliability aligns most closely with distribution-side grid reliability metrics representing the supply reliability of the electricity access solution. The experienced reliability concept then adds demand-side components relevant to households' experiences of their electricity. Section 5.3's differentiation of the reasons for outages and their quantitative analysis in Section 5.4 expand upon and justify this terminology. For if power technically available, but not accessible to households, the goals of SDG 7 will not truly be achieved.

Reviewing the methods used for measuring reliability in literature

The majority of existing reliability literature investigates issues in developed countries by evaluating bulk power system reliability trends over space and time [46, 47], predicting interruptions using maintenance or weather data [48], or evaluating the impact of renewables [49]. A more recent trend distinguishes resilience from reliability (Hossain et al., 2021). Fewer studies empirically evaluate reliability on electricity grids or decentralized energy systems in developing countries, and no prior reviews of methods exist. In response, Table 5.1 summarizes the academic literature that evaluates reliability in developing countries, highlighting the methods and metrics used. The review used the following inclusion criterion: peer-reviewed journal articles or conference papers, published between 2010 and 2021, provided an empirical evaluation of reliability, and located in a developing country. This review primarily focuses on studies located in SSA and is only representative (not comprehensive) of the extensive literature located in India or literature that relies exclusively on surveyed reliability.

Table 5.1 confirm's Kennedy et al.'s finding that most studies survey respondents for their perception of power availability. Accurate values of reliability from individual recall are notoriously poor therefore limiting the insights available from survey-based studies [50].

In Table 5.1, articles separated by the category and specific type of metric used, and whether the focus is on centralized or decentralized systems. Each article is denoted by its data collection method whether through interviews or surveys (S), physically measured (M), modelled or optimized (O), or measured using a proxy (P). The World Bank Surveys used later this chapter are included here as reference points. For similar literature that did not meet the inclusion criterion: [21] presents an exhaustive review of articles that optimize or simulate systems in these contexts and use reliability as a constraint rather than evaluating it empirically. [33, 34] include additional economic literature that uses survey and panel data to investigate the impact of unreliability on economic growth. See [18, 70] for literature on

Category	**Metric**	**Literature - Centralized Grid**	**Literature - Decentralized**
Duration out	SAIDI	Ayaburi 2020 – S; Klugman 2019 – MS; Taneja 2017 – SP; WB Doing Business Survey	
	Hours out	Correa 2018b – M; Farquharson 2018 – S; Moyo 2013 – S; Niroomand 2020 – S; WB Enterprise Survey	Moharil 2010 – O; Numminen 2019 – S
Duration on	Availability	Adair-Rohani 2013 – S; Agrawal 2020 – S; Aidoo 2018 – SP; Chakravorty 2014 – S; Graber 2018 – S; Harish 2014 – O; Kennedy 2020 – S; Murphy 2014 – O; Pelz 2021 – S; Sharma 2020 – S; Thomas 2018 – S	Adair-Rohani 2013 – S; Aklin 2021 – S; Aklin 2016 – S; Barman 2017 – S; Numminen 2019 – S; Numminen 2018 – M; Graber 2018 – S; Harish 2014 – O; Murphy 2014 – O; Sharma 2020 – S
	Hours at peak	Graber 2018 – S; Sharma 2020 - S	Graber 2018 – S
Frequency	SAIFI	Ayaburi 2020 – S; Klugman 2019 – MS; Taneja 2017 – SP; WB Doing Business Survey	
	Days with an outage	Mann 2016 – P; Thomas 2018 – S	Aklin 2021 – S; Aklin 2016 – S; Numminen 2018 – M
	Outage Rate	Andersen 2013 – S; Correa 2018a – M, Chakravorty 2014 – S; Gertler 2017 – M; Molebe 2018 – M; Niroomand 2020 – S; Taneja 2017 – SP; WB Enterprise Survey	Murali 2015 – S; Numminen 2018 – M
Demand	Peak deficit	Harish 2014 – O	Harish 2014 – O
	Fraction or probability of serving demand		Kanase-Patil 2011 – O; Lee 2014 – O; Lee 2018 – O; Moharil 2010 – O

Table 5.1: Literature that empirically evaluates reliability in developing contexts uses diverse methods [12, 15, 16, 20, 22, 25, 31–36, 39, 44, 45, 50–69]

power quality issues in similar contexts. The ESMAP MTF's attributes would be considered to encompass the 'availability', 'hours at peak', and 'days with an outage' metrics [14].

While Table 1 shows a diversity of metrics used in academic literature, the global prevailing metrics are defined in the IEEE 1366 Guide for Electric Power Distribution Reliability

Indices [71]. These metrics represent the total duration (SAIDI, Equation 5.1) and frequency (SAIFI, Equation 5.2) of electricity interruptions normalized per customer over one year, where an interruption is a total loss of electrical power ignoring power quality issues [71]. See Appendix B for detailed methods. Therefore, SAIDI can be interpreted as the total hours of outages experienced by an average customer in one year, and SAIFI as the total number of outages experienced by an average customer in one year. Their strength lies in their ability to compare the reliability of different sized electricity systems by normalizing by customers served.

$$SAIDI = \frac{\sum Customer\ Minutes\ of\ Interruption}{Total\ Number\ of\ Customers\ Served} \tag{5.1}$$

$$SAIFI = \frac{\sum Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} \tag{5.2}$$

The World Bank's Doing Business Survey has increased the prominence of SAIDI and SAIFI in the developing world [72]. By rating and ranking countries around the world on the ease of doing business, the World Bank strongly influences global regulatory policies and investments [73]. 'Getting Electricity' is a major rating topic, and it includes SAIDI and SAIFI as reported by local utilities.

Methods used for measuring reliability in this chapter

The following analysis uses data-intensive methods informed by related literature to measure and compare the reliability of experienced household electricity access using common frameworks.

SAIDI and SAIFI Status Quo Comparison

There is a clear opportunity to document the reliability of decentralized systems alongside their local grids in peer-reviewed literature using the well-respected and widely used IEEE metrics. Table 1 finds no other articles that calculate SAIDI and SAIFI using the IEEE standard for decentralized systems using measured data, therefore further highlighting the unique contribution of this work. Therefore, this preliminary analysis of the reliability of household electricity access in Tanzania, Kenya, and India provides a status quo analysis and calculates SAIDI and SAIFI from empirical data using the validated IEEE 1366 modeling approach transparently detailed in Appendix B. However, there are challenges in applying these standard metrics designed for large, grid-scale power systems in wealthier countries to smaller electricity systems (including decentralized systems) in developing countries. In addition, none of the metrics of which the authors are aware of consider the distributional effects, causes, or timing of outages motivating the proposed metrics in later in this Section and analysis in Section 5.4. The remainder of this section summarizes how SAIDI and SAIFI are defined in the standard, indicating when their interpretation needs further refinement for energy systems in developing countries and for decentralized systems providing energy access.

First, since SAIDI and SAIFI were designed to represent the quality of a provider's normal operating service, their calculation in IEEE 1366 included a statistical method to distinguish and remove the effect of extreme events, or major event days (MED), that are out of the control of the provider. These include hurricanes, monsoons, and other large natural disasters [71]. Readers are referred to [41] and their extensive investigation of the impact of MEDs on reliability metrics in the US. The proceeding analysis follows the industry standard of reporting values excluding MEDs to investigate operating reliability.

Second, these metrics were designed to measure the delivery of electricity to paying customers. If a household does not have the means to pay for electricity even temporarily, and is therefore disconnected for non-payment, they are no longer included in the customer base. These 'economic outages' are still impactful and should be considered in a rights-based assessment of reliability such as that implied by SDG 7. They exhibit the distinction between provided reliable electricity and experienced unreliable energy poverty. However, in the absence of comprehensive data on the total household experience, reported reliability is approximated by excluding times when electricity use was limited due to non-payment. The absence of economic outages is a critical flaw in econometric literature that uses the prevailing metrics on a national-annual basis to investigate the impact of reliability on household economic growth, income, health, and education.

The third issue addressed is the unit of analysis, which is set at the household and/or meter. The IEEE standard defines one residential electricity customer as one meter or household rather than one individual. This chapter follows the IEEE conventions but recognizes the limitations of using the household as the unit of analysis in light of research and field observations on inequitable intra-household access to electricity, particularly for women and children [74–76].

Finally, in developing countries, the IEEE Standard may be less likely to be followed and automatic measurement is rare [44]; data limitations are more severe, including measurement, collection, and storage; and the outage profiles of off-grid solar + storage systems can be more representative of usage data than performance data [20]. In response to these challenges, this chapter uses transparent assumptions and standardized data management practices detailed in Appendix B and the Supplementary Information of the published journal article this chapter builds from. Doing so provides a uniquely systematic analysis that uniformly evaluates the reliability of decentralized and centralized systems providing energy access in Tanzania, Kenya, and India.

Proposed Metric 1: Reasons for the outage

Compiling these unique data sources and comparing the reliability across different scaled energy systems fills a critical gap in the literature's understanding of the reliability of SDG 7 in developing contexts. However, SAIDI and SAIFI values designed to measure grids alone fail to reflect many important aspects of households' experience of electricity reliability.

The case of decentralized systems makes apparent the need to differentiate between outages caused by different reasons.

In SHS, the reasons for electricity outages are very discernible to users. Resource outages begin when the battery runs out for the night and are resolved when the battery is recharged by the solar panel in the morning. Extremely cloudy weather, such as during monsoon season, may extend the duration of these outages to several days. Technical outages often occur suddenly caused by a short-circuit, over-voltage event, attempt at manipulation, or another technical malfunction. [22] additionally identified 'operational' outages where, for example, it takes several days for the correct personnel to arrive to the site to determine the technical outage reason, and more time for the correct part to be ordered and shipped to the rural energy system's location. Here, these are grouped into the duration of technical outages. Finally, this chapter identify and introduce the concept of economic outages, occurring when a PAYGo customer runs out of credit and resolves when the customer tops-up thereby restoring power. As detailed earlier, economic outages are never included as part of reliability evaluations of systems but are a crucial aspect of evaluating the household experience of electricity reliability.

Table 5.2 expands the outage categorization of SHS into a generalizable framework for energy systems across the continuum of solutions. For example, hydropower curtailed because of a drought would be considered a resource outage. With the dominance of hydropower in African grids, it is likely that resource constraints will only become more pronounced with climate change. Similarly, load-shedding because of capacity constraints is also considered as resource-driven because it derives from an imbalance between supply and demand. Planned outages are resource-driven because they could be modified or shifted[4].

Different scaled systems, particularly between off-grid and on-grid systems, will have different proportions of the three distinct outage categories, each necessitating different solutions. However, all reasons will be present for all types of systems, and all contribute to total experienced electricity unreliability. Charting a path to improved reliability for both households and system operators requires careful consideration of what characteristics of unreliability one wishes to address.

Proposed Metric 2: Timing of outages

The timing of power outages has been qualitatively asserted as important to the experience of reliability [40, 43, 46, 63], however empirical investigations of outage patterns or predictability are rare. The examples that do exist are sparce in details. For example, ESMAP's MTF only separates 'day' and 'evening' in the reliability attribute. [43] and [40] both note that the time of the day that outages occur and what backup fuels households use are key to understanding impacts. Moreover, timing is a broad category of analysis rather than any specific metric. The 'timing' of outages can include: the average/median start time of an

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[4] Both the IEEE 1366 Standard and The Doing Business Survey Methodology include all occasions when customers lose power including planned and unplanned outages, as well as load shedding in their measurement and calculation of SAIDI and SAIFI [72]

Examples across the scale of systems	**Resource** (generation) generally avoidable or shiftable through planning	**Technical** (transmission, distribution)	**Economic** (billing)
Off-grid SHS with PAYGo financing	Battery capacity runs out for the night, able to charge via solar the following day	Fault, broken electrical component	PAYGo customer does not put in enough credit for 24/7 access
Off-grid, diesel minigrid with post-pay billing	Diesel fuel unavailable because of transport difficulties (war, natural disaster, road blockages). Load shedding during peak hours due to capacity constraints	Fault, broken electrical component	Post-pay customers have electricity service cut off because of past unpaid bills
Grid with post-pay billing (Status Quo)	Hydropower curtailed because of drought. Natural gas or heavy fuel oil unavailable because of transport difficulties. Planned outages for regular maintenance. Load shedding due to inadequate generation	Fault, broken electrical component on transmission or distribution	Post-pay customers have their electricity service cut off because of past unpaid bills. Utilities with tariffs less than the cost of service use blackouts to limit losses

Table 5.2: Outage categorization framework for systems providing energy access.

outage, the consistency or predictability in that start time, the probability that an outage will occur, the value of the moment when an outage occurs, etc. Load based metrics in the IEEE 1366 standard [71] somewhat represent a revealed value of the time of day but consider each kVA of demand to be of equal value - omitting that a kVA for lighting or health might be considered higher value than a kVA for entertainment.

To examine multiple facets of the timing of outages, Figure 5.3 proposes two ways of depicting reliability timing. The first shows the probability of being in an outage state at each hour of the day. The second depicts the range of outage durations for each starting hour. These metrics are applied to the SHS, KPLC feeder, and ESMI Kenya datasets. This novel empirical work validates past model assumptions in literature about the temporal patterns of reliability [69].

Proposed Metric 3: Fairness of outage distribution

Of all the metrics proposed, the fairness of outage distribution has been the most previously researched, however never for decentralized systems. Heylen et al. (2019) reviews various fairness indices to assess the distribution of electricity reliability among end-users and recommends use of the Gini index and its corresponding Lorenz curves [42]. These indices are: i) the most used measure of inequality in economic contexts, ii) have transparent graphical representations, and iii) are easily interpretable and comparable. This proposed metric builds from [42, 77] to evaluate the inequality of electricity reliability across the presented datasets.

A typical Lorenz curve plots the cumulative share of the population on the X-axis against the cumulative share of income on the Y-axis. A perfectly equal share of income across a population results in a line with a slope of one. The greater the inequality in the sample, the more the curve bows down to the X-axis. Figure 4 adapts this method to show the cumulative share of the population of the energy system on the X-axis against a Y-axis measuring: A. the cumulative share of outage durations as a proxy for SAIDI, and B. the cumulative share of outage frequencies as a proxy for SAIFI. Formally, this Lorenz curve can be expressed as:

$$L(y) = \frac{\int_0^y x dF(x)}{\mu} \tag{5.3}$$

Where $F(y)$ is the cumulative, continuous, distribution function of customers arranged in increasing unreliability, and μ is the average.

Data Sources

The primary and secondary datasets detailed below should be viewed as a unique collection of case studies in a global study of the reliability of electricity access. Because of the variety across the case studies, conclusive statistical comparisons or generalizations would not be faithfully provided. Readers should not interpret values from the included surveys as truth that is directly comparable to measured data. Rather, their value lies in their ability to illuminate deeper understandings of reliability and patterns within datasets and broadly across the scale of systems. The data sets from SHS in Tanzania and grid feeders in Nairobi, Kenya are highlighted as novel primary data. Details on the scope, measurement, and links to availability of datasets are provided in Appendix B to assist future research, filling a crucial gap in the availability of electricity reliability measurements in developing countries. Figure 1 displays approximate locations of the energy systems studied.

The data sources below are organized first in terms of location starting with Tanzania, then Kenya, then India. Within each country, data sources are organized by system size (from smallest to largest) where available.

Decentralized solar-home-systems (SHS) in Tanzania

Off-Grid Electric Ltd. is an energy services company that provides home energy solutions based on solar and storage technologies and PAYGo micro-financing mechanisms across SSA. Data was collected from their solar-plus-storage kits that range from 30-120 Wh, that are designed to provide 24/7 power for lighting, charging, radio, TV, and other loads. The authors collected and summarized the primary system data for a non-random sample of 417 SHS installed across 16 regions of Tanzania.

Centralized grid in Tanzania

TANESCO is the national electric utility for mainland Tanzania. TANESCO's grid reliability is reported in two global surveys conducted by the World Bank included here as secondary sources: i) the Enterprise Survey [56, 78] is a firm-level, representative sample of an economy's private sector. Because businesses report their experienced reliability, this data is denoted as 'from Businesses'; ii) the Doing Business Survey [52, 72] annually collects an array of policy and process metrics relevant to starting and operating small and medium enterprises. Annual SAIDI and SAIFI values are requested from the distribution utility company in the largest business city of each economy. These data points are denoted as 'from utilities' because the utility reports its own reliability.

The Electricity Supply Monitoring Initiative (ESMI) led by the Prayas Energy Group [79] provides an additional secondary data source for the electricity grid in Tanzania through its real-time, open-source database on supply interruptions and voltage levels at consumer locations (households and commercial). Their pilot ran from January 2017 to May 2018 recording data at twenty-five locations in Dar es Salaam Tanzania.

Centralized grid in Kenya

Kenya Power and Lighting Company (KPLC) is the sole electricity distribution company in Kenya operating the interconnected grid as well as several regional grids in northern Kenya. Through a collaboration with KPLC's Institute of Energy Studies and Research, the authors acquired and summarized primary data on the reliability of seven 11 kV feeders in the greater Nairobi area between June 2017 and July 2018. Primary data on the counts of outage incidents on 323 feeders in Nairobi over a two-year period are also summarized. In addition to SAIDI and SAIFI collected from the World Bank Surveys, Kenyan grid reliability is measured by the ESMI Kenya Initiative on their fifty-nine sensors in residential locations in Nairobi between November 2017 and October 2018.

Decentralized solar-pico-grids (SPG) in India

Numminen et al. reported on reliability of seven low-power, direct current, solar-battery pico-grids in rural northern India [45]. The SPG supplied basic electricity services (lighting and phone charging) 24/7 but connections were limited to 30 W. The data summaries in Numminen's journal article and supporting documentation were summarized and reprinted with permission.

Centralized grid in India

Secondary data on SAIDI and SAIFI representing the electricity grid of India was compiled from the World Bank Surveys and from ESMI. ESMI has over 437 locations across twenty-three states in India, eighteen of which are within one-hundred km of Numminen's SPG in rural Uttar Pradesh. The data spans September 2015 to the writing of this chapter.

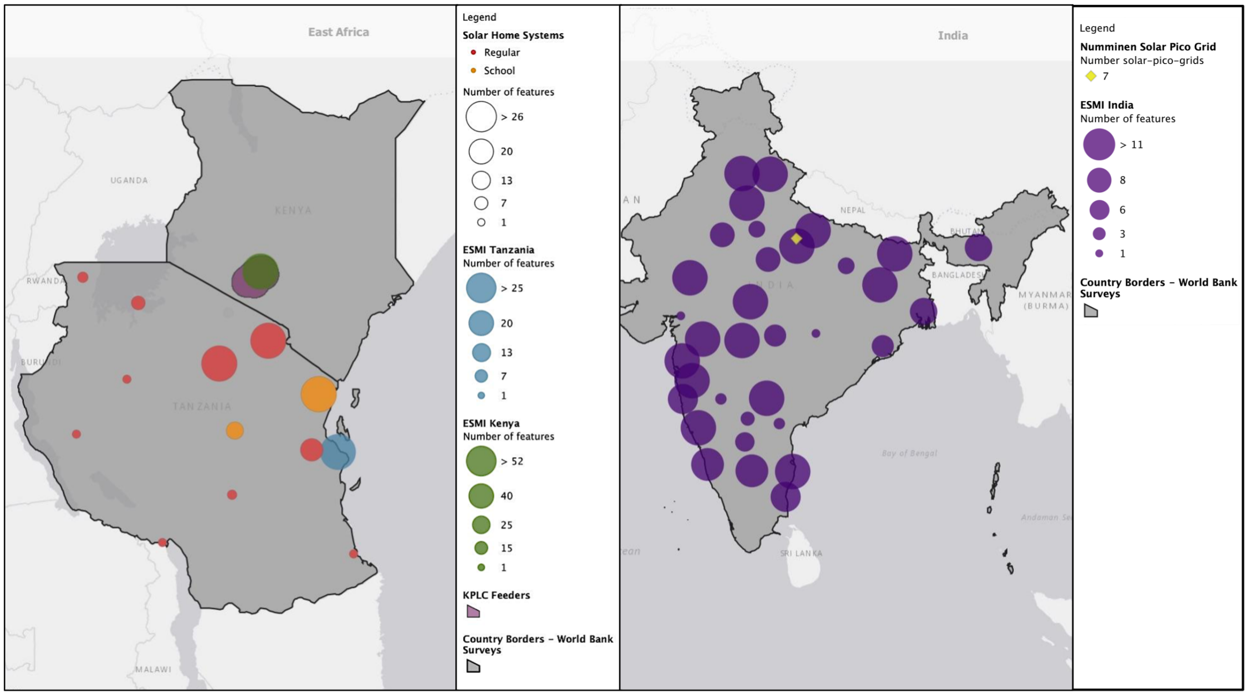

Figure 5.1: Approximate locations of data sources

Figure 5.1 displays the approximate locations of the above datasets. SHS in Tanzania are red and orange (distinguishing households and schools respectively); SPG in India are yellow diamonds; ESMI household grid sensors in are circles in Tanzania (blue), Kenya (green), and India (violet); buffers around KPLC Feeders in Nairobi are purple; and country borders represent the World Bank Surveys. The number of features represents the approximate numbers of sensors and is depicted by different sized icons. For all household systems, a random adjustment of 10km was added before clustering for confidentiality following the rural area methodology of USAID's DHS.

In summary, the SHS and KPLC data represent primary datasets collected by the authors; the SHS, SPG, and ESMI datasets were measured at residential household meters; The KPLC and Doing Business datasets were measured at grid-level sensors, and the Enterprise dataset was from a representative survey of business owners. All data sources are thoroughly described in SI for transparency. This chapter focuses on household-level experienced electricity reliability in Tanzania, Kenya, and India. In comparison to the considerable literature dedicated to SDG 7 overall, experienced household-level reliability is under investigated, particularly in East Africa. Rather than comparing customer classes, non-household measurements are interpreted as floors for residential SAIDI/SAIFI in those same locations.

5.4 Analysis, Results, and Discussion

The following analyses seek only to compare the experienced reliability of household electricity – measured intuitively by when households can turn on their lights – provided by the above systems supplying electricity access. Different scaled systems can power different types of loads, are priced differently, and range in the other attributes described by the ESMAP MTF. However, reliability comparisons using common frameworks still fill key gaps in the literature's understanding of the reliability of SDG 7.

Status Quo: Comparing SAIDI and SAIFI

Figure 2 reports the systematic calculations of SAIDI and SAIFI from each of the various datasets in Tanzania, Kenya, and India using methods detailed in Appendix B. Subsets are provided for regions with a separation between decentralized and centralized electricity sources.

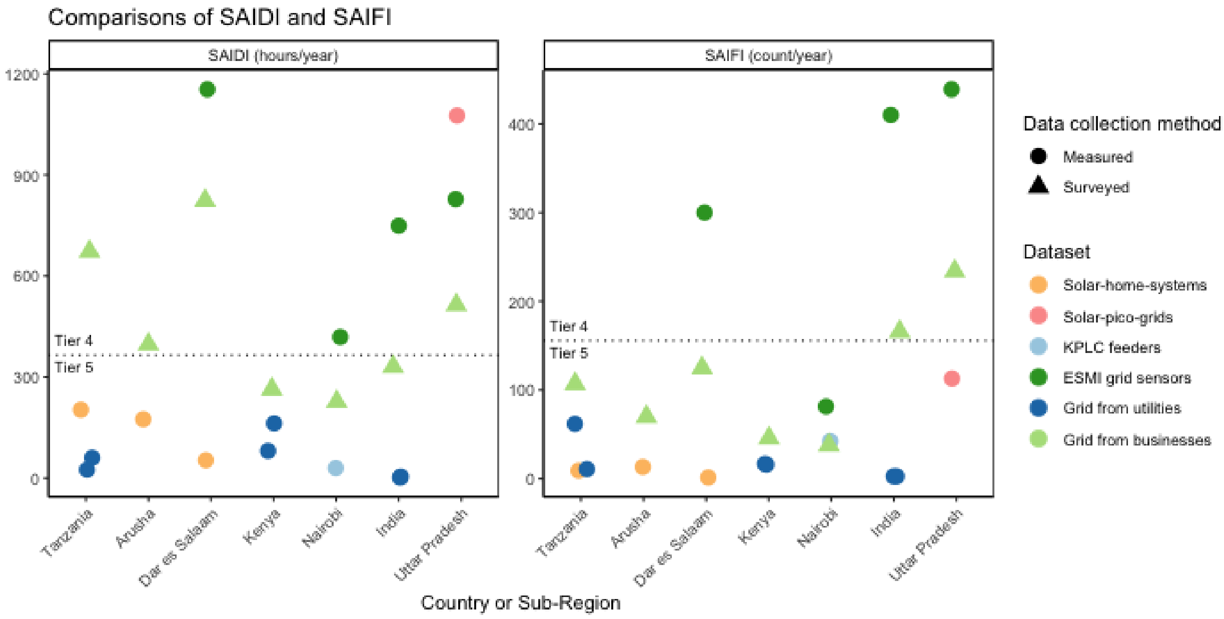

Figure 5.2: Status quo comparisons of SAIDI and SAIFI across all datasets in Tanzania, Kenya, and India and sub-regions

In Figure 5.2, decentralized systems are noted in warm colors (orange and pink) while centralized grid systems are in cool colors (greens and blues). Marker shape designates the data collection method. Horizontal dashed lines mark the threshold between Tiers 4 and 5 in the ESMAP Multi-tier framework. All values are taken from the closest period to 2016, are scaled by data availability to represent one full year and have momentary and MED cut-offs applied. For complete details see Appendix B.

An initial focus on the centralized grid reveals several interesting comparisons. The non-homogeneity of electricity reliability is made evident by the vast differences across sub-regions, depicting pockets of better (or worse) grid reliability. The data from the ESMI sensors exhibited the largest SAIDI and SAIFI in all regions and sub-regions. The next largest values were recorded through surveys of the experiences of businesses via the WB Enterprise Survey. Measured grid reliability in the same year and location reported by the national utility via the WB Doing Business Survey was often an order of magnitude lower than both the values from ESMI and the Enterprise Surveys. As reported by Taneja and Tait, there is significant reason to suspect utility-reported values as under-reporting actual outages because of either omission of low-voltage data collection by the utilities or flawed incentives of utilities reporting their own performance to potential sources of funding [43, 44]. Future research into the magnitude of under-reporting is necessary. Although caution must always be placed on data collected from surveys, the large difference between the reported reliability from the two World Bank surveys is still striking as also noted by [16, 44]. If the ESMI data is taken as representative of regional household electricity reliability, then the difference in reliability between ESMI and the customer surveys indicates that customers may in fact be significantly under-reporting grid unreliability, contrary to most literature that indicates that customers tend to overestimate supply problems [22].

The SAIFI and SAIDI from the KPLC feeder voltage data in Nairobi were 2 and 14 times less, respectively, than the SAIFI and SAIDI from the ESMI sensors also measuring the grid in Nairobi. The Doing Business Survey for the whole country, which came indirectly from the same utility, had a 170% higher SAIDI and 60% lower SAIFI than the KPLC feeders. Therefore, the KPLC feeder data was investigated to explain this divergence from the other datasets and to illustrate how three factors (the level of the electricity grid, geographic scope, and temporal granularity) to impact reliability measurement in the Supplementary Information of the journal article from which this chapter builds. In summary, sensors closer to residential households (in terms of geographic proximity and similar lower-voltage levels) and measured at higher temporal resolution reveal higher numbers and durations of outages. This indicates that in order to evaluate the experienced household electricity reliability for SDG 7, high temporal and spatial resolution data directly measured at the household level is necessary.

A focus on decentralized system reliability reveals comparable reliability to their local and national grids. In the first documented empirical evaluation of the reliability of SHS in a developing country, SHS had fewer outages than the local grid, even by the grid's own reporting. The annual duration of outages for SHS was dramatically lower than the other household-level datasets in all three locations. The SAIDI achieved is equivalent to approximately fifty-six minutes of outage per customer per day. When comparing SAIFI between the grid and SHS, and when examining a regional comparison of SAIDI and SAIFI in Arusha, SHS performed significantly better than the grid in terms of reliability. The SPG reported by Numminen showed a slightly larger SAIDI than the other datasets, but a SAIFI slightly less than the other results from Uttar Pradesh. These findings uniquely contribute to the literature on decentralized energy system reliability in developing countries and show promising results for decentralized solar energy systems to be able to provide reliable electricity for household lighting.

While promising, these results do not necessarily imply that decentralized systems are better overall choices based solely on their improved reliability. The other indicators in ESMAP's MTF such as quality, capacity, and safety, and affordability are all vital parts of the comparison and are evaluated in more detail elsewhere [17, 39]. This chapter seeks only to inform the reliability aspect of the larger frameworks.

However, these empirical results do reveal important gaps in the existing frameworks for measuring SDG 7. Based on measured duration and reliability, SHS would supply Tier 5 service on the ESMAP Multi-tier Matrix for Access to Household Electricity Supply but would be categorized as between Tiers 1 and 2 due to capacity [14]. Numminen's pico-grid achieves Tier 5 service for reliability, Tier 4 service for duration, but only Tier 1 access for capacity [45]. While many of the local grids would supply Tier 5 capacity, they only provide Tier 4 reliability based on surveys and meter-level measurements. Therefore, the notions of reliability in ESMAP's MTF do not necessarily line up with the reality of deployed systems. While grids in developing regions tend not to meet reliability or affordability constraints, the SHS may meet reliability but not capacity goals. The existing thresholds in the MTF need continuous updating as more reliability data becomes available, and as energy efficiency improvements continue to provide more value from less power.

Comparisons on proposed metrics

SAIDI and SAIFI values alone fail to reflect three key aspects of outages: the reasons for the outages, the timing of the outages, and the fairness of outage distribution throughout the community. These aspects have been alluded to but are rarely empirically examined in literature. The industry standard metrics are further insufficient because they were designed to measure centralized grids rather than the newer renewable energy-based, stand-alone, or decentralized systems. This chapters's unique collection of datasets highlights the disparities in these three vital aspects of reliability - all of which are indispensable when comparing the household experience of reliability of across the scale of energy solutions.

Reasons for outages

At present, it is only possible to separate the contribution of different outage reasons for the SHS dataset, particularly to distinguish resource from technical outages in measured reliability, as well as represent the additional toll on households from economic outages. Table 3 shows that while most of the events were resource-based, the total duration was dominated by economic outages. In all three cases, the median was less than the mean with large standard deviations indicating wide distributions that are skewed right. Unlike other SHS studies, battery degradation was not a concern because the systems in question used high-quality lithium-ion batteries and were leased on an energy-as-a-service model.

Outage Reason	**Event count**	**Duration of events, in minutes**		
		Mean	Median	Standard deviation
Resource	1106	737	456	2,886
Technical	48	14,258	4,050	27,660
Economic	478	16,347	4,550	25,061

Table 5.3: Descriptive statistics of SHS outages separated by the reason for the outage. MEDs and momentary events removed.

Of the 203 hr/yr/household SAIDI (median = 0, standard deviation = 756) (representing only resource and technical outages with MEDs and momentary interruptions removed), 54% is attributed to resource outages. Including economic outages instead of considering them unavailable time increases annual household electricity unreliability four times. Affordability is thereore a major part of household experienced reliability on these pre-paid systems. In other words, while customers perceive technical outages to be the most concerning, they are smallest contribution to experienced unreliably for SHS households. Because outages due to individual customers' economic challenges are not associated with utilities' supplied reliability, the remaining results will not include these outages when comparing the reliability of other energy sources. Unfortunately, other case study datasets do not contain information on the economic status, or payment records, of the individual households or customers, therefore patterns cannot be drawn across economic classes.

A recent UN Report on SDG 7 found that, "The number of people without access to electricity increased in 2020 after declining over the previous six years, due to population growth and increased costs for basic electricity services, which are now unaffordable for more than 25 million people who had previously gained electricity access. An additional 85 million people, mainly in developing Asia, could lose the ability to pay for an extended bundle of electricity services and may therefore need to scale back to basic electricity access" [4]. When the presented concept of economic outages is placed against Gertler et al. (2017)'s analysis on the negative economic impacts of outages, a negative feedback cycle becomes apparent [32]. These cycles, also called vicious cycles [80] are created when poor system reliability leads to depressed economic circumstances, leading to low ability to pay, and therefore more economic outages. Recognizing and quantifying economic outages will only become more important for understanding the depths of energy poverty in the future.

Recent efforts to upgrade components, improve maintenance, and build necessary generation and transmission capacity across grids in SSA promise to decrease the frequency and duration of both resource and technical outages. Improvements in these categories of outages, or efforts to shift peak demand, do not erase the existence of distinct categories of outages, only their proportions and timing. The analyses presented in this chapter present a snapshot of outage durations, frequencies, reasons, timing, and distributions from the case studies at the time of collection. Specific values are expected to change over time. In the near term, continued monitoring will be needed across all three categories of outages to improve real-time reliability investments. Moving forward, this analysis framework will be essential for making long-term comparisons and guiding policy to address the most pressing issues.

Timing of outages

Examining the timing of outages – in terms of the hourly outage state probability and hourly outage duration - shows strongly different patterns depending on the dataset and reason for the outage, demonstrating the value of this proposed metric. Figure 5.3.A-B show the hourly probability of being in an outage state described by the range of locations and the customer-weighted mean. The feeders show a bimodal pattern with a higher probability of being in an outage state between 4-6 am and 9-10 pm. The higher probability for those hours is equivalent to one day in three-and-a-half months in an outage state. Both outage periods have a high likelihood of large impacts on residential consumers, especially 9-10pm which overlaps with peak demand from the feeder load data. If outages on the utility grid are primarily technical outages due to random events, a flatter distribution would be expected. However, the bimodal pattern suggests that outages are more dependent upon usage patterns than purely random events, potentially also implying load shedding during times of peak load. The grid-connected household data has a much flatter distribution with slight increases between 10am and 5pm.

In Figure 5.3, two proposed metrics applied to each dataset show the importance of considering outage timing. Figure 5.3.A-B on top depict the probability of the Nairobi grid being in an outage state for each hour of the day from two different datasets. Figure 5.3.C-E on bottom depict the durations of outages starting during each hour of the day. The box-and-whisker plots display the median and range, and the red dots display the customer-weighted mean. Differences between the median and mean indicate significantly skewed distributions.

The depictions of outage duration by starting time in Figure 5.3.C-E are indicative of the architecture of the different systems and the reasons for their outages. The SHS show a clear decreasing trend for resource outages with a maximum median outage duration of 15 hours at 5pm, a minimum median outage duration of 3 hours at 1pm, and a wider range of outage durations between 3-5pm. This pattern results from the SHS's ability to recharge during the day, but if a resource outage starts at sunset (nominally 6:30pm year-round in Tanzania), then the outage will last until the system can recharge when the sun rises approximately 12 hours later. The minimum median outage duration represents the amount of time needed for the batteries to recharge enough for users to regain access to electricity, not necessarily to fully recharge the batteries. The feeder and grid-connected household results do not show such clear patterns. The durations of outages on grid-connected households are notably much larger than those on grid feeders or SHS.

There are several important ways that this proposed approach can be used for real reliability improvements. By correlating outage incidences and durations with the time of the day and load, the utility – or other energy system provider - can better direct investments

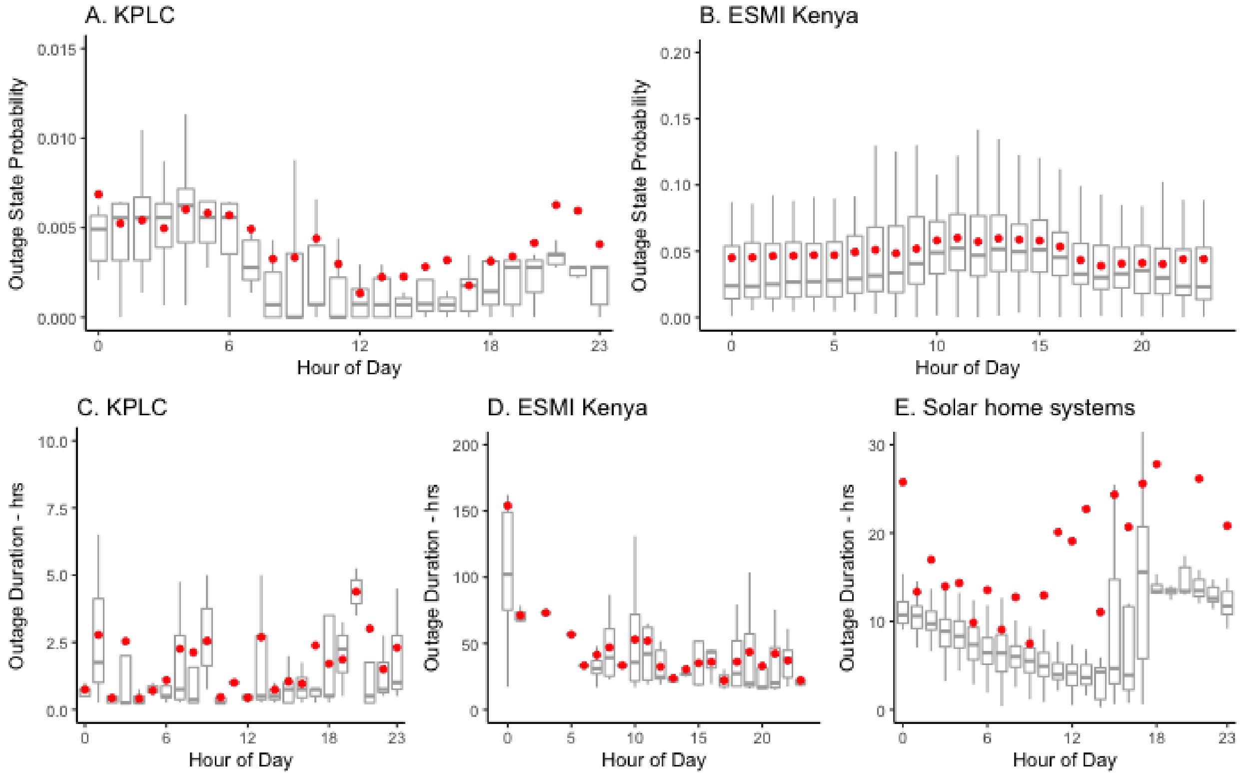

Figure 5.3: Timing of outages for SHS, KPLC, and ESMI Kenya datasets

towards fixing those that impact reliability the most. For example, frequent load shedding indicates inadequate generation capacity or transmission constraints, while more random events during those same peak-load hours, may indicate specific overloaded equipment that needs upgrading. This proposed analysis can also inform more practical policies such as real-time, dynamic maintenance schedules that determine how many maintenance workers are needed to respond to outages occurring at different times of the day and night, and how maintenance equipment should be stationed throughout a city. Understanding the causes of outages combined with their timing is useful because it points to different sets of 'technological, economic, or political solutions' for improving reliability [32]. For SHS, this analysis can be used to identify ideal customers for upgrades in addition to informing solar-to-battery ratios optimized for customer user patterns. Ideal customers to upgrade have few economic outages (indicating sufficient ability to pay) but many resource outages, particularly in the evening (indicating i) insufficient battery sizing for their usage if batteries are fully recharged daily, and/or ii) insufficient solar capacity if batteries are not fully recharged daily). The systems in question were fully recharged daily, indicating battery sizing was the more severe constraint. Customers on systems with more predictable outage patterns at the same SAIDI and SAIFI levels are more likely to be able to access the benefits of electricity.

Fairness of outage distribution

In addition to intra-household access fairness mentioned earlier, there is also a need for increased emphasis on inter-household fairness. Both Aidoo and Briggs (2018) and Dunn et al. (2019) explore spatial and temporal disparities in grid outages in different settings and with different methods. Aidoo and Briggs used messages to the Dumsor Report in Accra, Ghana to evaluate the degree to which rolling blackouts disproportionately hurt poorer neighborhoods. They found that daily, the poorest housing quintile received an average of 7.5 hours of electricity while the richest received 17.5 hours even though 12 hours were pledged equally to all neighborhoods. The top residential and commercial tax class received electricity nearly 24/7 [59]. An examination of the ESMI Kenya data found that 'low income' households received over twice the outage duration and frequency as 'high income' households in Nairobi, Kenya. Dunn et al. used grid outage data scraped from the websites of utilities in the Western United States and found that grid performance spanned orders of magnitude within service territories, uncovering significant policy implications [46].

The Lorenz curves in Figure 5.4 show surprising and important results for both outage counts and durations. Although Aidoo and Briggs noted dramatic differences in outage durations between poor and rich neighborhoods in Ghana, their data (reproduced with permission) had the most equal distribution of the datasets presented [59]. The SPG had the most equal distribution of outage counts, partially attributable to system's architecture where customers are cut off jointly during an outage. The SHS, in both counts and duration, had the least equal distributions of outages, with many systems having no outages over their sample period. While perfect reliability is an ideal, due to the nature of battery-constrained systems, a SHS user only receives a resource outage if they have used all the daily kWh available. Therefore, a household with a fixed system size receives more kWh (therefore, benefit) from their SHS when they have more resource outages. The variation within the ESMI datasets and between the datasets located in Kenya were also noteworthy. Of the ESMI datasets, the distributions of outage durations and counts for India were more unequal than the distributions for Tanzania and Kenya, which is attributed to geographic scope. The 437 sensors in India are located across twenty-three states, while the 59 sensors in Kenya and 25 sensors in Tanzania were all located in Nairobi and Dar es Salaam respectively. While the KPLC voltage data and KPLC incident reports (both for the greater Nairobi area) showed similar outage count distributions, and the KPLC voltage data and ESMI Kenya data showed similar outage duration distributions, the KPLC voltage data and KPLC incident reports had less-equal distributions of outage counts than the ESMI Kenya data. This difference is particularly notable because the KPLC feeder voltage was measured at a higher level of the grid than the household-level ESMI Kenya data, therefore it was expected for there to be more shared outages and more similar outage durations between feeders.

In Figure 5.4, adapted Lorenz curves show the cumulative share of the population of each system on the X-axis against a Y-axis measuring: A. Cumulative share of outage durations as a proxy for SAIDI. B. Cumulative share of outage frequencies as a proxy for SAIFI. Each available dataset is presented along with a black line with slope=1 representing the

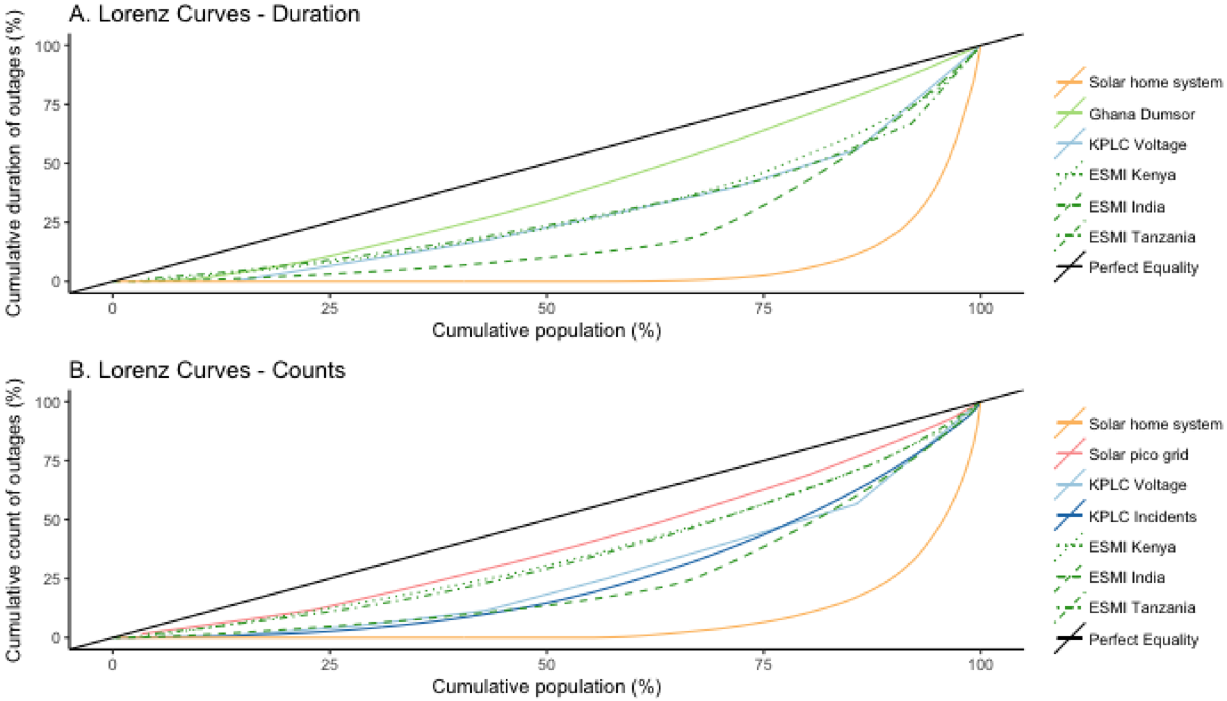

Figure 5.4: Comparison of energy system reliability inequality using Lorenz curves

ideal, perfect equality of outages. Blue and green lines represent grid datasets, while orange and pink represent decentralized systems. 'Ghana Dumsor' is summarized and printed with permission from Aidoo and Briggs (2018).

These proposed metrics show that the current metrics, SAIDI and SAIFI, are not sufficient for describing the reasons for outages, the timing of outages, or the fairness of outage distribution on individual electricity access solutions and therefore across the continuum of options.

5.5 Policy implications for addressing energy poverty in the Global South

The above empirical analysis provides crucial insights into the reliability of experienced household electricity access in Tanzania, Kenya, and India. These findings suggest several immediate policy implications and underscore the need for further work to understand the unreliability of household electricity access across the scale of solutions.

> *Implication 1: Studies that evaluate the impacts of unreliability need high temporal and spatial resolution data directly measured on the communities of interest.*

Prevailing methods use nationally aggregated annual SAIDI or SAIFI to evaluate business and economic development. This aggregation fails to adequately represent the magnitude, range, and nuance of reliability, therefore obscuring insights. Without an understanding of the timing of outages and alternatives available to end-users, the prevailing methods are severely lacking.

> *Implication 2: For household electricity access in particular, the existing reliability metrics (SAIDI, SAIFI, Multi-Tier Framework) are insufficient for informing SDG 7 policy decisions.*

Existing metrics measure reliability of supply rather than experienced reliability (when the lights are on for households rather than when the system could supply power, i.e., the combination of resource + technical + economic outages). SAIDI and SAIFI are not designed to measure decentralized solutions which will play a prominent role in energy access efforts alongside grid extension, particularly in the short term and in rural areas. Households will nearly always have poorer electricity reliability than nearby urban and/or industrial customers.

> *Implication 3: The affordability of energy access solutions is already becoming as important as access to the solutions.*

In the only data set available that had visibility into economic outages, they composed up to three quarters of experienced unreliability. The UN reports that the number of individuals who are losing their access to electricity due to affordability issues is increasing. As households are becoming increasingly responsible for procuring their own access in a marketplace, affordability is surpassing availability as the dominant barrier to universal electricity access.

> *Implication 4: Fairness and equality must be at the forefront of efforts to improve the service quality of electricity solutions in Sub-Saharan Africa.*

Fairness and inequality are not typically considered when reliability enhancement decisions are made. Future investments and upgrades can prioritize increasing these aims such that a base level of service is achieved for all. Not considering them harms the chances of achieving SDG 7's mission, particularly reliability for all.

5.6 Limitations and opportunities for future research

There are a few important directions for additional investigation to build from this chapter. Namely: the importance of qualitative research; balancing reliability with cost, particularly for SHS and SPG; addressing load-limiting procedures in reliability analysis; and distinguishing the reliability effects of stacked systems. Quantitative assessments, such as provided here, will benefit from more qualitative and human-facing research into subjective experiences of electricity reliability. Emerging literature such as [18] and [22] are excellent examples of research creating qualitative and subjective indicators of reliability grounded in fieldwork and interviews. Measuring reliability in ways that account for both providers and customers perspectives can be an important way of minimizing biases.

As noted above, the reliability of any stand-alone, solar-plus-storage system is dependent upon usage patterns. For example, SHS customers who use their system more will have more resource-driven outages when their battery runs out for the night. This can mean that reliability data can be more representative of usage data than system performance data [20]. Although the ratio of the solar and storage can always be modified to reduce outages, some customers may find it more beneficial to have a cheaper system that is used to its full capacity. Some of the existing literature on decentralized minigrids addresses this tradeoff between cost and technical reliability, [20, 69] but further community-facing research is needed to address how this trade-off plays out in the design, selection, and use of SHS and SPG.

Another limitation is that outage statistics do not reflect load-limiting procedures. The SHS studied here (as well as Numminen's SPG in India [22, 45] and Quetchenbach's micro-hydro minigrid in Bhutan [70]) limit household loads when they are capacity constrained and threatened by resource-driven outages. Although these procedures allow individuals to receive some energy services (generally lighting), they are prevented from using larger appliances. This suppressed demand is generally not considered an outage even though the experience is significantly affected. Future research on the behavioral dynamics between load-limiting procedures and demand-response-type behavior by individuals to reduce the occurrence or effects of load-limits is crucial.

Finally, there is a trend towards energy system stacking for improving overall experienced reliability. In India, it is not uncommon for off-grid-systems, minigrids, and the national grid to operate side by side in unreliable-grid areas, and for some customers to have connections to all three [81]. While the analysis here omits stacking effects, future work on household experienced reliability should address stacked systems, especially to evaluate the revealed willingness to pay for added reliability. Nigeria, a country with low grid reliability and a large reliance on back-up systems, offers an ideal location. Readers are referred to analyses such as [25, 61, 62] for examples in India.

5.7 Conclusion

This chapter fills key gaps the field's understanding of the electricity reliability of energy access in developing countries by providing one of the first detailed evaluations of measured SHS reliability in SSA in peer-reviewed literature and highlighting the importance of economic outages. It provides a representative review of the existing empirical literature; compiles a unique collection of datasets in a global survey of energy access; and proposes a common framework to analyze outage causes, timing, and the fairness of outage distribution.

The above case studies show that SHS provide comparable reliability to their local grids, but the distributions of outages were less equitable than for other sources. Grid reliability measurements are highly sensitive to geographic scope, temporal granularity, and the level of the electricity grid, causing orders of magnitude differences between values. Outages can be categorized as resource, economic, or technical, each which have different timing patterns and outage distributions. And finally, economic outages, conspicuous in PAYGo SHS customers' experienced reliability, compose a significant portion of experienced unreliability and are severely underrepresented in reliability metrics and broader reliability literature.

While the SAIDI and SAIFI results from the presented datasets are compelling, they are insufficient for understanding household electricity reliability in isolation. The magnitude of electricity unreliability in developing countries and the entrance of decentralized technologies highlight the limits of existing metrics. In failing to account for the reasons, timing, or distribution of outages, SAIDI and SAIFI are insufficient for comparing the household experience of reliability of energy solutions and prioritizing solutions. This chapter's outage categorization framework, presentation of outage timing, and use of the Lorenz methodology to examine outage inequality are generalizable for use by future researchers.

Since reliability is defined to measure how well the provider is supplying power, it does not necessarily represent the recipient's experience. For example, the inclusion of economic outages increased experienced unreliability by a factor of four. Since reliable electricity is an enabling factor for nearly all Sustainable Development Goals, if individuals are still not receiving reliable power, these outages should also be quantified and addressed.

This research provides an example of the insights available when reliability data is made public, bolstering calls for all stakeholders to quantify and share data on the reliability of electricity systems and include reliability in energy access policy and regulation.

In these efforts, there will be a tension between the need for increased emphasis on reliability and an overreliance on any individual metric. In an era of increasing quantification, while metrics for easy comparison are seductive, they can lead to oversimplification and homogenization if not grounded in qualitative understandings [82]. Ongoing qualitative scholarship on understanding energy poverty alongside energy literacy efforts for households in encouraged alongside transparency and standardization (as well as acknowledgement of nuance) in reporting practices throughout the sector. These are necessary, but not sufficient, first steps towards understanding the full landscape of electricity reliability from which future work can find where simplifications are, or are not, appropriate.

Lee et al. (2019) details the opportunities and risks for key stakeholders from increased data sharing in the context of expanding electricity access. They note that standardization and transparency into the reliability of electricity products allows individuals to make the most informed decision. This transparency allows for increased competition between providers resulting in better services provided for end users and allows governments, investors, and development institutions to encourage the best performing systems through performance-based regulation and investment [28]. This chapter's study demonstrates the possibilities and insight gained when full detailed data is available, however rare. The appropriate balance between the complexity of data needed to measure reliability accurately, and simply communicating findings to policymakers and households can be found only after the full landscape is made apparent.

In the discourse of energy access policy, modeling, and literature, centralized and decentralized solutions are rarely compared on equal footing, even though in many cases they are already working in concert to achieve improved energy access across communities and within households. As decentralized energy systems actively redefine how millions receive electricity access, they can also redefine how the sector measures, compares, and regulates access. This study uniquely demonstrates how distributed solar technologies can be compared to utility electricity and can contribute to household electricity reliability in developing communities to truly achieve "access to affordable, reliable, sustainable and modern energy for all."

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Chapter 6

Leaving communities of color in the dark: Rotating outages in California create energy and social injustices

Preface

The third and final application chapter examines the energy equity implications of the rotating outages in California in August 2020.

Take a moment to imagine yourself as one of hundreds of thousands of Californians on August 14th and 15th, 2020. For the past five months you have been sheltering at home due to the global pandemic but state COVID-19 cases and deaths are still at an all-time high. An extreme heat storm covered the entire western US and dry thunderstorms sparked quickly growing wildfires which threatened homes and elevated parts of your state to have the worst air quality on record. Then your power is turned off by your utility, right when you need it most to power your AC, air filters, medical equipment, and communications.

These Californians experienced rotating power outages when electricity demand exceeded available capacity during the climate change-induced heat storm. This particular type of outages are supposed to be "short and shared" and therefore are generally considered equitable. They are implemented by regulated agencies acting in the general public's interest to avoid grid-wide brownouts. However, my work reveals an inequitable distribution of this burden as a consequence of implementation and procedural decisions. This final application of quantitative methods to energy justice investigates the extent to which communities across California were differentially affected by the climate-disaster provoked rotating power outages in terms of distributional and procedural tenets of energy justice with significant policy implications.

We thereby investigate the inequitable distribution of the energy burden of rotating power outages. In particular, we draw on Chapter 3's discussion surrounding the distinction between equal and equitable, and methods such as t-tests and correlations.

Abstract

This research examines the extent to which communities across California were differentially affected by the heat-wave-provoked rotating power outages in Fall 2020 viewed through lenses of distributive and procedural justice. We find statistically significant and severe energy injustices across racial and ethnic lines. Across different decision-making levels of rotating outage planning and implementation we find higher proportions of the population self-identifying as Asian, Hispanic, and Black. While eligibility speaks more to injustices surrounding population dynamics and access to essential infrastructure, notification and suspected experience reveal energy inequities unexplained by other compounding factors, and which place disproportionate burdens on some communities of color. These types of outages are meant to be 'short and shared,' so while mitigating factors such as income and health are also observed, strong racial signatures are of concern. These outages are implemented by regulated agencies acting in the general public's interest to avoid grid-wide brownouts, therefore, there are immediate policy implications to ensure equitable decision-making during future climate disasters.

6.1 Introduction

In August and September 2020, Californians faced a staggering array of compounding threats. An extreme heat emergency covered the entire western United States with temperatures 10-20 degrees above normal (See Figure C.3) [1], dry thunderstorms sparked quickly growing wildfires which elevated parts of California to have the worst air quality on record, and the COVID-19 pandemic raged across the country. It was in this context that hundreds of thousands of Californians faced rotating power outages, which we find revealed significant and severe energy injustices. While the outages were implemented by agencies ostensibly acting in the public interest to avoid grid-wide brownouts, the implementation decisions placed disproportionate burdens on the shoulders of communities of color. While changes in infrastructure investments can legitimately take time, this work provides public oversight agencies and committed companies immediate opportunities to implement equitable actions and policy changes. This analysis:

- Uses basic statistical methods to investigate the equality and equity implications of these outages, which can and should be performed by any number of stakeholders;
- Finds that rotating power outages posed significant and severe racial and ethnic injustices and therefore should be more strongly regulated; and
- Proposes policies that are needed to ensure that burdens are equitably shared during extreme events which will become even more prevalent with climate change.

The climate change-induced heat storm resulted in electricity demand exceeding available supply in California's grid during the early evening hours by increasing electricity demand, reducing available imports, and causing temperature-related transmission constraints. Outdated resource adequacy and planning targets and practices in the day-ahead market exacerbated these supply challenges [1]. Despite a series of pre-emptive actions designed to maintain electricity system reliability, the California Independent System Operator (CAISO) was forced to declare a Stage 3 Emergency on August 14th and 15th in order to stabilize the grid and avoid cascading uncontrolled outages. CAISO thereby ordered all three of California's Investor Owned Utilities (IOUs) - Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E), and Southern California Edison (SCE) - to initiate rotating outages across their service territories on a pro-rata basis (e.g. each utility sheds load in proportion to their total load). Furthermore, on August 17th and 18th, 2020, September 5th and 6th, 2020, and July 9th, 2021, similar circumstances forced CAISO to declare up to Stage 2 Emergencies where the threat of rotating outages was imminent, but not implemented [1, 2].

This chapter's investigates distributive and procedural energy justice concerns resulting from these rotating outages across the service territory of the largest IOU in California, PG&E (Figure 6.1a). Our quantitative distributive justice approach geospatially combines rotating outage threat and census data to statistically evaluate inequities across race, income, and other population dynamics. Additionally, we examine potentially compounding environmental stressors such as CalEnviroScreen, air quality, and maximum temperature during the outages. Our qualitative procedural justice approach examines the process for determining rotating outage plans and priorities, thereby aligning this research with the decision-making processes and producing actionable policy recommendations.

6.2 Rotating outages as energy justice concerns

Energy justice has emerged as a modern focus of environmental and climate justice that refers to "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" [3]. The core theoretical approaches to energy justice include: distributive justice - how benefits and burdens are distributed; procedural justice - who is included in the decision-making process; recognition justice - how to understand historic and ongoing inequalities; and restorative justice - how to avoid or correct for past injustices [4, 5].

Our analysis is informed by theories of distributive energy justice (the unequal distribution of modern energy services and burdens across society) and procedural energy justice (due process, representative justice, and justice as public participation). Distributive justice is often broken down into three aspects: what goods are distributed, between what entities, and what is the proper mode of distribution whether based on need, merit, or other factors [6]. Procedural justice centers around who gets to decide and set rules and laws, which parties are recognized, by what processes, and how impartial are those involved [6]. It also includes procedural transparency and follow-through. We add a theoretical and methodological contribution to the quantitative energy justice literature by making explicit the difference between equality and equity, explained at the end of this section.

Unlike other types of power outages in California that are locationally specific and occur because of distribution failures, unpaid bills, uncontrolled grid destabilization, or wildfire-prevention Public Safety Power Shutoffs, these rotating power outages present a singular opportunity to examine how power outages were intentionally distributed across California's communities. Rotating outages (also known as load shedding, forced reduction, dropped load, or emergency electric load curtailment) provide a broadly shared benefit through a localized energy burden, thereby setting the stage for potentially unjust distributions. An overall stable electricity grid during electric capacity shortages is ensured by selectively de-energizing portions of the customer population. While CAISO orders the IOUs to implement rotating outages on a pro-rata basis (e.g. each utility sheds load in proportion to their total load), the IOUs internally determine how they distributed those outages across their service territory [1, 7, 8] with little operational oversight.

The existing process of spreading outages on a rotating basis is generally considered fair because the outages are relatively short and shared [8, 9]. Ideally, a list of eligible areas is fully rotated through giving all an equal chance of bearing the localized burden for the benefit of the entire service territory. However, these were the first rotating outages since California's 2001 electricity crisis [2], and affected only 11.1% of PG&E's residential electric customer base [1]. At this rate of outages, assuming two-thirds of customers are eligible, it would take 114 years to rotate through the full list. There were thus policy-based choices made about where the outages should go, and where they should go first. Whether implicitly or explicitly decided, we found significant and severe inequalities across the communities threatened by these outages. These actions violate notions of distributive justice where these explicitly shareable energy burdens were not shared equally, and were disproportionately placed on the shoulders of communities of color.

By receiving federal financial assistance, the energy sector is subject to Title VI of the Civil Rights Act of 1964 which states "no person in the United States shall, on the ground of race, color, national origin, be excluded from participation in, be denied the benefits of, or subjected to discrimination under any program or activity." Executive Order 12898 and the accompanying Presidential Memorandum in 1994 focused federal attention to the environmental justice effects of federal actions. And for California, Senate Bill 115 defines and coordinates environmental justice efforts for the state.

Despite this long legislative precedent in the United States, environmental, climate, and energy injustices are all too common. Recent scholarship has documented the disproportionate burden faced by communities of color and other vulnerable communities both in the current status of service provision and in the potential for future impacts under climate change [10]. Literature focusing on residential rooftop solar in the US typifies patterns found across the energy sector. For example, Sunter et al. (2019) assesses rooftop photovoltaic deployment by race and ethnicity across the US and finds significant racial disparities in installations even after accounting for differences in household income and homeownership [11]. Brockway et al. (2021) further reveals that limits inherent to grid infrastructure exacerbate the above inequalities reducing future access to new solar photovoltaic capacity for Black-identifying and disadvantaged census blocks [12].

Beyond rooftop solar access, African American populations have been found to bear the foremost burden of energy injustices as seen through disproportionate siting of locally unwanted land uses (toxic waste dumps and landfills, incinerators, interstate highways, industrial facilities, and power plants) [13], higher likelihood of disconnection notices and utility shut-offs [14], less energy efficient households [15], and higher proportion of income spent on energy bills [16]. However, many of these issues also apply to low-income groups, the elderly, those with disabilities, women, and other non-white populations [10]. The need to apply justice principles to federal investments and policy in energy, infrastructure, and emergency management is clear.

This work contributes to a growing body of literature on inequalities in access to reliable electricity in the United States, particularly during times of crisis. Dunn et al. (2019) documents the spatial and temporal variability of electricity grid reliability across one of the largest utility territories in the US. They find that grid reliability spans orders of magnitude across the service territory with significant inequalities between rural and urban areas [17]. Liévanos and Horne (2017) analyze inequalities in electricity outage duration at a census block group level between 2002 and 2004 [18]. Several studies including Tormos-Aponte et al. (2021) study the extensive power outages in Puerto Rico in the wake of Hurricane María, examining the political and demographic determinants of government responsiveness during the disaster recovery process [19]. Finally, gray literature examines inequalities across the blackouts in Texas in 2021 [20].

We acknowledge that the average rotating outage durations were relatively short, however these outages occurred during extremely high value hours. The interconnected risk of an extreme heat wave (necessitating air conditioning and fans), wildfires (necessitating communication technology for evacuations and air filters for smoke), and COVID-19 (necessitating communication technology and complicating any population movement for relief from the heat and fires) each magnify the impact of not having power for those hours. The scale and impact of rotating outages comprised of:

- *August 14th, 2020* — 300,600 customers, 588 MW, 150 minutes, 4.8% of August 2020 peak demand in forced outage
- *August 15th, 2020* — 234,000 customers, 459 MW, 90 minutes, 4.4% of August 2020 peak demand in forced outage
- Combined, just over 11.1% of PG&E's total residential electric distribution customer accounts. PG&E's 2021 Corporate Sustainability Report listed 4.8 million residential accounts. Note: 'Customer' should be interpreted as 'meter' rather than individual, therefore the total number of people affected is multiples larger than the 534,600 combined sum.
- These events will raise the company's reliability metric, SAIFI, by 0.03 (2.6% of PG&E's 2019 outages per customer) [9]

Excess heat is intimately linked to excess death, particularly for minority communities [21]. In fact, no other category of hazardous weather event in the United States has caused more fatalities over the last few decades than extreme heat. Its impact is magnified for communities with pre-existing health conditions (e.g., chronic obstructive pulmonary disease, asthma, cardiovascular disease, etc.), limited access to resources, and the elderly [22]. Further, research examining the effects of racist historical housing policies (aka. redlining) on present-day urban temperatures find significant heat disparities in all studied cities in California [22]. Electricity is one of the most accessible mitigating factors for avoiding extreme heat, and heat is one of many climate events that disproportionately hurts vulnerable populations. Therefore studying who has their power shutoff during a climate emergency gains significant importance for those specific events and for informing climate disaster response more broadly.

The disproportionate health risk when power is shut off under extreme heat motivates this chapter's application of the theoretical distinction between equality and equity proposed in Gill-Wiehl et al. [23]. That article's conceptualization of energy equality is derived from John Rawl's primary goods approach [24] where every individual has a minimum level of said good. Their conceptualization of energy equity draws on Amartya Sen's [25] and Martha Nussbaum's [26] capabilities approach where every individual receives according to the level needed to enable the individual to achieve equivalent capability.

Therefore, a rotating outage plan that gives all eligible customers an "equal chance of being curtailed" [8], can result in severely inequitable outcomes when there are large differences in customers' ability to accommodate the curtailments. When certain communities are at much higher risk of death when their electricity is cut off, an equal distribution of outages is not an equal distribution of risk, nor an equitable distribution based on capabilities. This chapter's first quantitatively examines distributive justice in terms of equality of rotating outages. We then expand our analysis towards equity by including normative claims of vulnerability and adaptive capacity.

6.3 Quantitative geospatial distributive justice approach

To gain insight into the distributive justice implications of the August 2020 rotating outages across PG&E's service territory, we combined publicly-available geospatial shapefiles of rotating outage blocks[27] with census demographic data and environmental risk vulnerability at the census block group level (Figure 6.1).

The (2009-2019) American Community Survey (ACS) 5-year Estimates Detailed Tables for 2019 provides ethnicity and race (Figure 6.1b), income (Figure 6.1c), health, and educational attainment at a census block resolution for the state of California. The 2019 ACS 5-year Estimates has the advantages of being temporally closest demographic data available to the outage events, increased statistical reliability over 1-year estimates, and has the same census block group geographies that would have been available to rotating outage planners. ACS median income at a census block resolution was then combined with county-level required annual income from the Living Wage Calculator to create a surplus income category to account for the widely ranging costs of living across the state.

Environmental risk is identified through environmental justice scores as well as maximum temperature and air quality during the event. The California Communities Environmental Health Screening Tool: CalEnviroScreen 4.0 identifies census tracts in California that are disproportionately burdened by multiple sources of pollution (Figure 6.1e) [28]. Scores range from 0 (lowest burden) to 100 (highest burden) describing relative impact of pollution from exposures, environmental effects, sensitive populations, and socioeconomic factors.

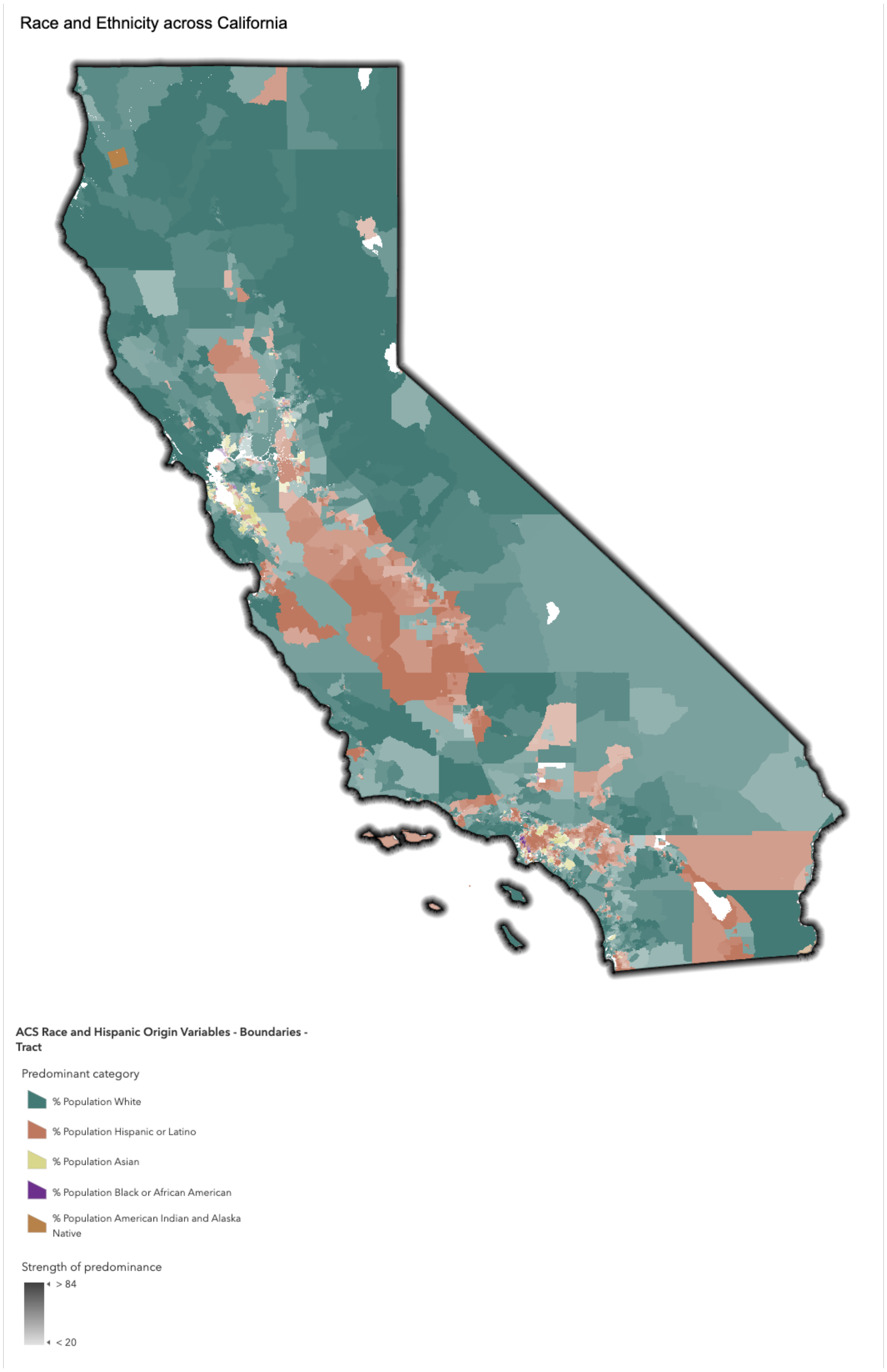
Beyond the stationary measures of environmental risk depicted by the CalEnviroScreen, future work will incorporate dynamic metrics from the dates of the events for a more accurate picture of the exposed risk at the time of shutoff. Maximum temperature and air-quality during the shutoff periods would be particularly important for these events which occurred during - and because of - an extreme heat emergency and quickly growing wildfires.

Census block groups are a contiguous cluster of census blocks within a census tract and generally consist of between 600–3000 people. Rotating outage block groups can generally be defined as several streets [27], or distribution grid circuits of similar size to census block groups. We geospatially assigned demographic and environmental risk variables to rotating outage shapefiles by first assuming spatial homogeneity of demographics within census block groups. Demographic variables interpretable by total numbers were then summed within the proportional area of overlap between census block groups and rotating outage shapefiles. Demographic variables not interpretable by a total number, such as median income, were averaged within rotating outage shapefiles using population weights.

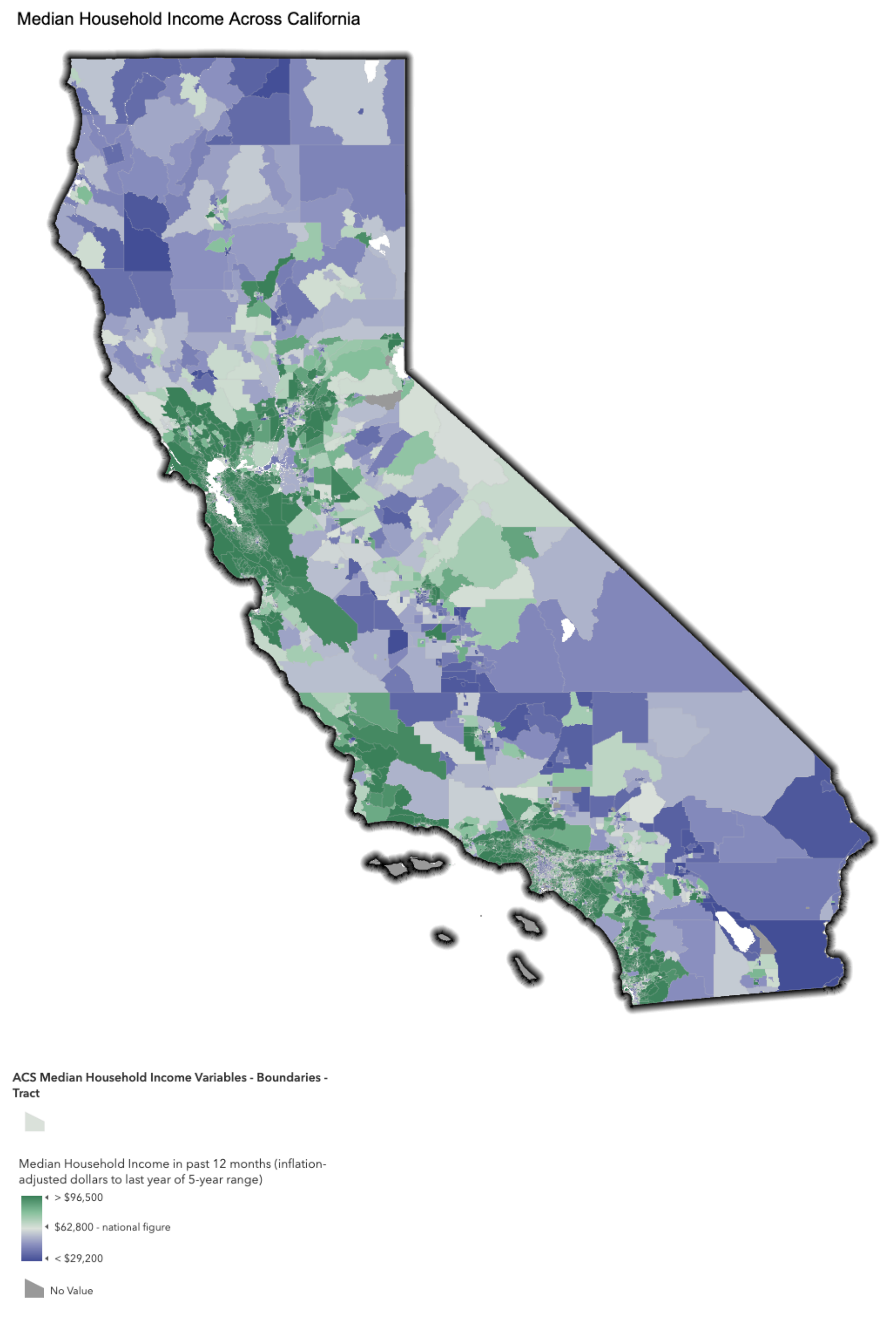
Shapefiles that were assigned populations consisting of less than ten individuals, or that were excluded from the CalEnviroScreen scoring because of exclusively non-residential usage were removed from this analysis. Therefore, the resulting dataset describes the spatially-weighted average demographic and environmental risk values of 10,890 rotating outage block observations. Descriptive statistics of the evaluated populations are summarized in Table

6.1. The study area is defined by geographic areas within PG&E's service territory that were identified in both a census block group and a rotating outage block shapefile.

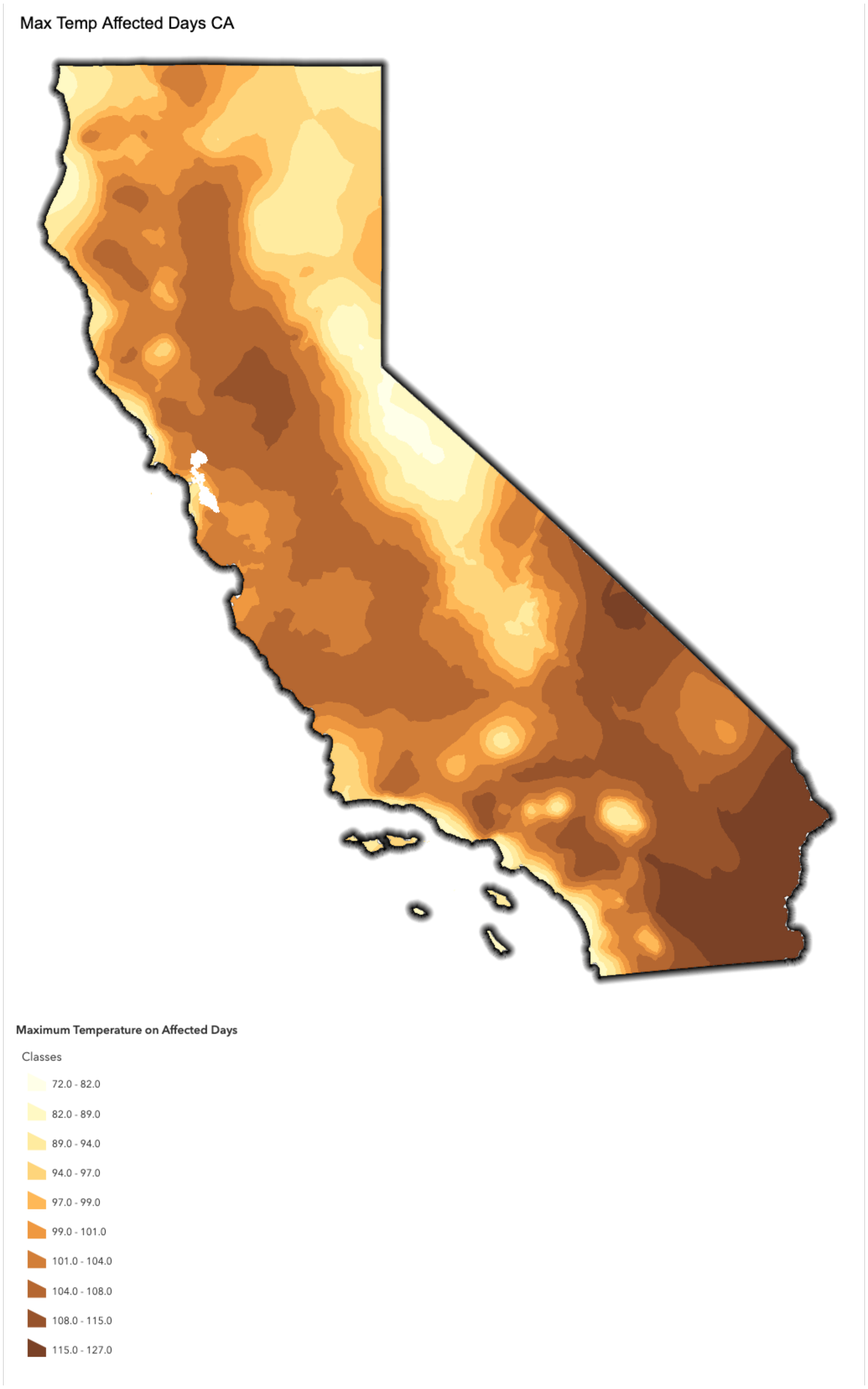
(a) PG&E Service Territory



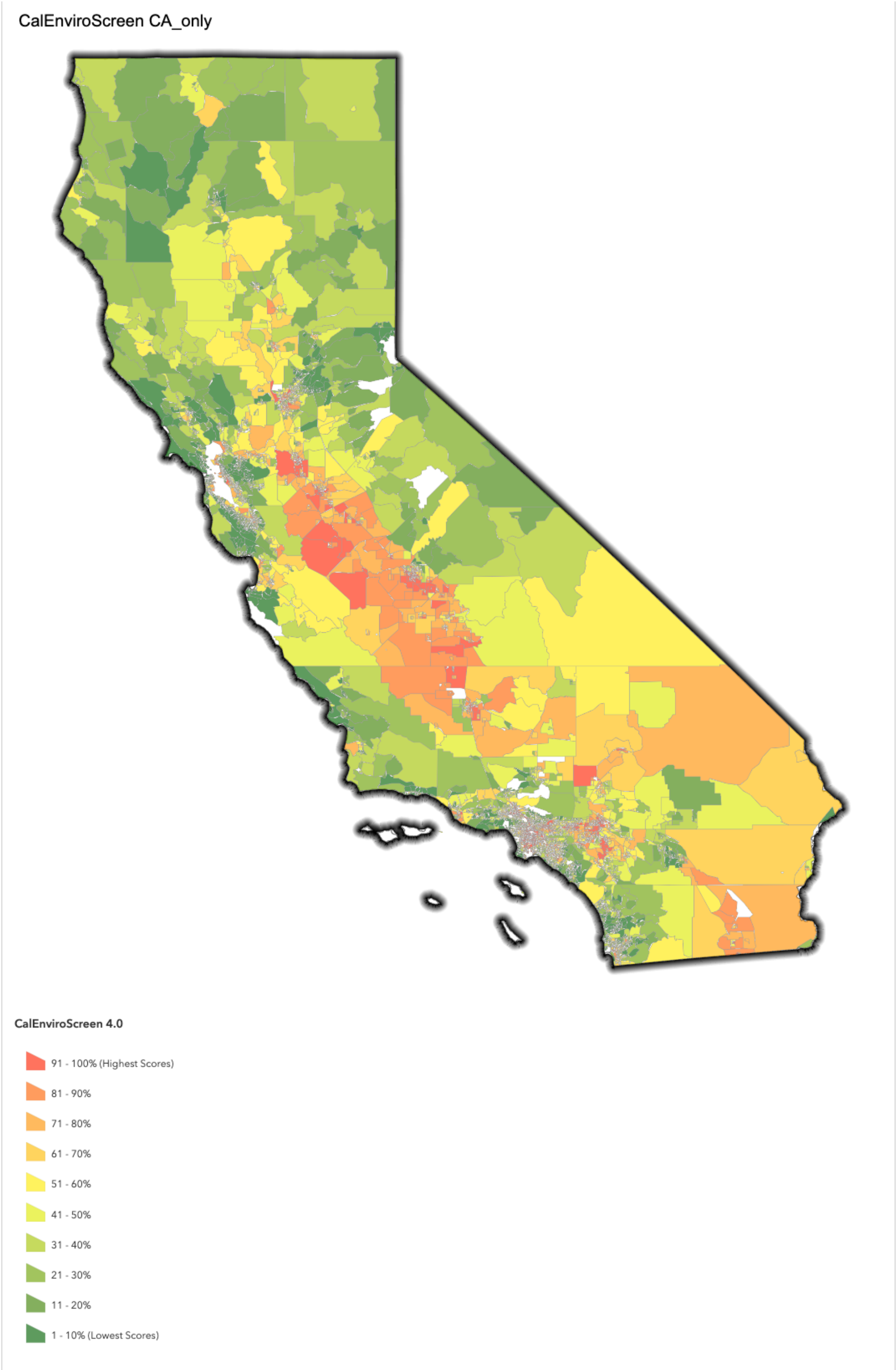
(b) ACS Race and Hispanic Origin



(c) ACS Median Household Income



(d) Maximum Temp on Event Days



(e) CalEnviroScreen 4.0

Figure 6.1: Geographic Scope and Demographic and Environmental Risk Data

A unique contribution of this quantitative energy justice analysis is its alignment with decision making steps in the utility's planning and implementation process, enabling findings to inform future action. We therefore define for the readers three distinct levels of decision-making and analysis at which we compare demographic and environmental risk variables. Each level is investigated sequentially. Figure 6.2 visually depicts the separation of all rotating outage block groups into nested categories from lowest risk of experiencing rotating outages (left) to highest risk (right). The horizontal widths are proportional to the total number of blocks in each category. The horizontal widths of the categories in Levels 1, 2 and 3a are proportional to the total population in each category. The left-most red arrow in Level 3b is only approximate but indicative of other populations experiencing rotating outages who were not necessarily notified of imminent outages. While Levels 1, 2, and 3a are investigated quantitatively, Level 3b is investigated qualitatively.

- *Level 1 evaluates rotating outage eligibility.* Approximately one third of the study area population resides in areas that are exempt from receiving outages because they share a circuit with essential customers or critical facilities such as "a hospital, police station or fire department [27]." The remaining population is considered eligible for rotating outages. This analysis reveals demographic disparities primarily resulting from the utility's current definition of essential infrastructure. Our subsequent policy analysis suggests how different definitions of 'essential' may result in a more equitable eligibility distribution.
- *Level 2 evaluates notification of imminent outages.* All eligible blocks are given an alphanumeric identifier that describes the order in which blocks are shut off in the event of rotating outages. Approximately half of all eligible blocks were notified of imminent outages (placed on standby) between August 14-15, August 17-18, September 5-6, 2020 and July 9th, 2021. This analysis reveals direct documentation of the differential rotating outage prioritization of demographic groups.
- *Level 3 evaluates rotating outage implementation.* Approximately one tenth of notified blocks are suspected of having received rotating outages based on publicly available data. Level 3a provides a quantitative analysis describing how this first tenth of notified blocks differs from other notified and/or eligible blocks. However there is substantial evidence described below that the suspected blocks were not the only ones to have their power shut-off, necessitating Level 3b's qualitative investigation. These analyses reveal distributive and procedural issues surrounding which blocks were first in line or receive outages, and to what extent the emergency load curtailment plans were followed.

Each analysis level utilizes methods specific to the decision-making process to evaluate energy justice implications. Binary Groupings such as Level 1: Eligibility versus Exemption, Level 2: Notification vs No Notification, and Level 3a: Suspected Experience vs other Eligibility use standard student t-tests, weighted t-tests, and descriptive summations to compare continuous demographic and environmental risk variables across rotating outage block

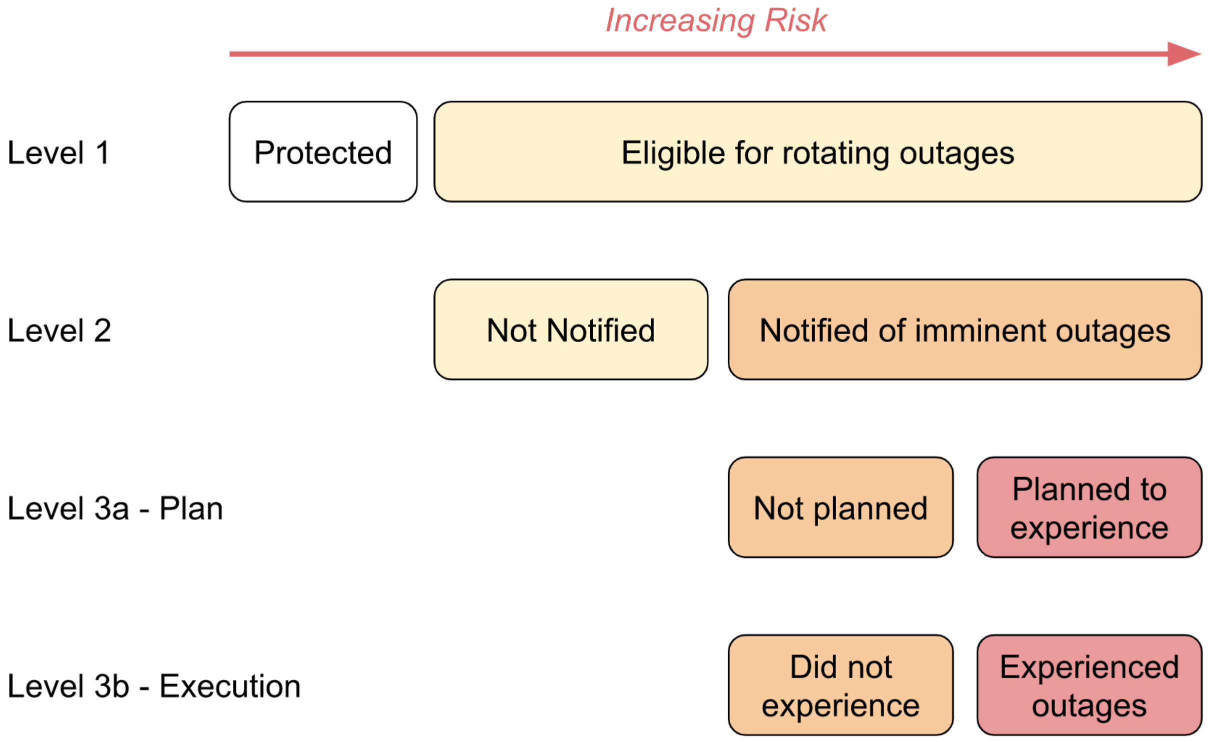


Figure 6.2: Levels of Analysis

categories. For the statistical tests, we assume the null hypothesis $H0$, that *There is no difference in demographic and environmental risk variables between treated and untreated groups, where treatment corresponds to the assignment of rotating outages.* In other words, that rotating outage assignment was equal across demographic and environmental risk. The t-tests therefore indicate the probability that disparities in the variables are due to chance alone. The sample sizes are sufficiently large to meet the gaussian distribution assumption. Our subsequent discussion uses the following notations for statistical significance: * for P ¡ 0.05; ** for P ¡ 0.01; and *** for P ¡ 0.001. A strict Bonferroni multiple-significance-test correction is applied at each level of testing which adjusts the 0.05 significance level to 0.05/(12 tests) = 0.004166. Continuous outage risk variables such as demographic and environmental variation along the rank order of rotating outage blocks within Level 2: Notification, is quantified using regressions and visualized through locally weighted scatterplot smoothing (LOWESS).

The functional forms of the above quantitative approaches more accurately measure the equality of this energy burden across different communities. This analysis takes an additional step to also evaluate equity of outcomes. For example, a t-test result with sufficiently dramatic magnitude of difference indicates that an inequality was present. Statistical significance indicates that we can reject the null hypothesis that the finding was only due to random chance. When results are significant and large and they compound reduced adaptive capacity to deal with a power outage during a heat wave, we label these disparities as inequitable. We rely on Thomas (2019) to define reduced adaptive capacity and increased vulnerability to harm from climate change. They find increased vulnerability among U.S. non-white populations, those with lower-incomes or in poverty, women, the uneducated, those linguistically isolated, and the disabled [29]. Such dramatic underlying differences in adaptive capacity across populations allows for 'objective' or vulnerability-blind adaptation planning approaches to further exacerbate inequalities in access to resources.

Category	**Statistic**	**Overall**	**Range**	**Median**	**S.D.**
	Total Population	Total: 12,522,068	[10 - 24,136]	105	2,439
Race and ethnicity	*Percent Hispanic*	31.3 %	[0 - 100 %]	23.3 %	25.0 %
	Percent non-Hispanic White	41.5 %	[0 - 100 %]	38.7 %	24.4 %
	Percent non-Hispanic Asian	17.7 %	[0 - 98.1 %]	11.9 %	18.8 %
	Percent non-Hispanic Black	4.7 %	[0 - 73.3 %]	2.3 %	8.2 %
	Percent of other races	4.7 %	[0 - 84.1 %]	4.2 %	3.7 %
Income	*Median Income*	$88,426	[0 - $248,125]	$80,988	$46,852
	Surplus Income	$16,662	[-73, 205−172,020]	$9,150	$40,113
	Percent below poverty line	13.5 %	[0 - 85.0%]	10.3 %	11.4 %
Health	*Percent above 65 years old*	14.3 %	[0 - 96.2 %]	12.8 %	8.1 %
Education	*Percent adults with no HS edu.*	10.6 %	[0 - 66.5 %]	7.8 %	9.1 %
Environmental Risk	*CalEnviroScreen 4.0 Score*	26.8	[1 - 93.2]	23.6	16.22

Table 6.1: Descriptive statistics of study area population across rotating outage block shapefiles

6.4 Quantitative distributive justice findings

Unless otherwise noted, all of the findings described in the text below had p-values at or below an adjusted significance level of 0.004166. We limit our discussion to test results that were significant using the standard student t-tests (our more conservative criteria) and of a magnitude larger than 5% different. However, we explain the results using the weighted mean percent of the population (wmpp) from the weighted t-tests (which were all significant at p ¡ 0.004166) for ease of understanding. The following findings are visualized in Figure 6.3, and supplementary Figures C.1, C.2, C.3, and C.4.

Outage eligibility disproportionately affects Asian population

Eligibility and exemption status are driven directly by proximity to essential infrastructure. Electrical grid circuits are exempt from rotating outages if they have a police station, hospital, or other essential infrastructure located on them. When residential areas are located on the same circuits, they are also exempt. Therefore, this level of analysis documents injustices driven by prior, non-energy, policies more than in energy decision-making during climate crises.

Because exemption is mechanistically assigned by the presence of essential infrastructure on the same circuit, there is no underlying uncertainty or random process (on the part of the utility) used to assign eligibility or exemption. Therefore, statistical tests are less appropriate than raw comparisons of summations or means. Therefore this section compares the weighted means of our demographic and environmental risk variables between eligible and exempt groups without reference to their statistical significance.

When we compare eligible blocks to blocks exempt from receiving outages, we find that the wmpp identifying as Asian was 20.5% larger (1.205 times) in eligible areas than in exempt areas. To put this number into context, non-Hispanic Asian-identifying individuals were 12.5% more likely than the average total population to be eligible for rotating outages. Further indicating inequalities, the wmpp identifying as Black was 11.0% higher (1.11 times) and the wmpp identifying as White was 10.2% lower (0.898 times). Black-identifying individuals were 6.3% more likely than the average population to be eligible for rotating outages, and White-identifying individuals were 5.2% less likely. However, several mitigating factors were identified at this level. The wmpp considered elderly (over 65) was 8.6% lower; the wmpp disabled was 14.6% lower; and all three income metrics were mitigating for eligible areas. The wmpp in poverty was 9.3% lower, the weighted mean median income was 6.53% higher, the weighted mean surplus income was 23.2% higher and the strongest mitigating inequality. These results are displayed in the left column of Figure 6.3. See Figure C.1 and C.2 for more details.

These findings are in alignment with Liévanos and Horne (2017) in that rational bureaucratic decision-making drives inequalities in outages [18]. However, proximity and access to essential infrastructure are themselves not non-political processes. We therefore encourage future research to combine research on inequitable access to essential services to examine how it mediates further climate emergency vulnerability.

Figure C.4 uses 2018 ACS census data to examine the maximum temperatures during the outage period by majority ethnicity. Majority is defined by one of our five racial/ethnic categories composing more than 50% of the population of that rotating outage block shapefile). Across all locations and days, we found a consistent trend of eligible blocks having higher max daily temperatures than exempt blocks with the same majority ethnicity. Future work will investigate this intersecting risk in more depth.

Notification of imminent outages disproportionately affects disabled populations

The next level of analysis compares the ordering of blocks of those that are eligible, thereby examining the equity implications of decision-making within the utility's rotating outage planning process. We assume that there is underlying uncertainty in the assignment of prioritizing different rotating outage blocks justifying the use of statistical tests.

First, we analyzed the binary distinction of blocks notified of imminent outages (the first half) to blocks that were not notified (the second half). Only two criteria were statistically significant at an adjusted p-value of 0.004166 using the standard t-tests. Of eligible areas, the percent of the population that is disabled was 5.83% larger in Notified areas than in not notified areas, however the wmpp reduces to 1.17% larger. Disabled individuals are often highly dependent on electrically powered medical equipment and are therefore less capable to safely withstand power outages. CalEnviroScreen scores indicated some mitigating effects where the weighted mean CalEnviroScreen score was 2.0% less for Notified areas than for other eligible areas that were not notified. Other binary results at this analysis level were not noteworthy either because they were not statistically significant or of small magnitude.

As displayed in Figure C.4, the 2018 census and maximum temperature analysis found that the maximum temperature was lower for White-majority blocks that were notified of imminent outage than for not notified blocks. However the maximum temperature was much higher for notified Black-majority blocks than for not notified ones.

Next, for eligible areas, we examine how the moving average of each demographic or environmental risk value changes as the risk of outage increases. These patterns are visualized using locally weighted scatterplot smoothing (LOWESS) in the middle column of Figure 6.3. Each LOWESS in black uses a bandwidth of 0.1 and the blue shading represents the 95% confidence interval. Risk of outage, determined by the rank order of the rotating outage block number, increases from left to right. Vertical lines separate rotating outage blocks based on (left) notification of imminent outages and (right) suspected of having experienced the rotating outages.

The LOWESS curves do not show unambiguous systematic leftward increasing trends across demographic and environmental risk variables which may indicate entrenched equity issues. However they do demonstrate significant variability along rank-ordered risk. This indicates that depending on where the cutoffs lie, the differences in mean demographics (such as those described by the t-tests) will change. The notification and suspected experience cutoffs were determined by how much capacity needed to be dropped to stabilize the grid. Other circumstances could easily have changed these precise cutoffs.

Another interesting observation of the LOWESS curves are the sharp changes of direction at the leftmost ends at the highest risk rotating outage blocks. Of the non-parametric curves, LOWESS is the most resilient to tail-wagging effect. Further the 95% confidence intervals do not dramatically spread, indicating a level of certainty of these direction changes. However, the direction of change for the LOWESS curves does not always align with the direction and magnitude of the results in the right-most column of the Figure 6.3 described in the next section. Since so few blocks are shut-off for each rotating outage event, one would hope that the swings remain small so that the average affected demographic is closer to the mean of the population rather than the outliers. Further investigation is needed to explain these effects and investigate why the moving averaged variables changed so much at the highest risk groups.

Future work will use regressions to investigate correlations between our demographic and environmental risk values and the risk of outage described by the rank order of the rotating outage block number among eligible blocks.

The rank order of all eligible blocks is a factor that is easily changeable by the relevant decision makers, namely the emergency load curtailment plan writer of the utility. In examining equity along the entire list of eligible rotating outage blocks, we thereby can predict the equity implications of future events as the utility rotates through their list of eligible.

Suspected experience of outages mitigated affects on Black populations

There is evidence that at least the first ten of the listed rotating outage blocks received outages during the August 2020 event. Therefore, while the past two levels quantitatively examine inequities in risk, and potential for future inequities, respectively, the following analysis examines experienced inequities.

In the strongest mitigating finding in our analysis, the wmpp identifying as Black was 44.9% lower in blocks suspected of having experienced the outages than in other notified blocks. Our summation results show that if one was Black in PG&E's service territory during this time you were 29.3% less likely than the average population of notified blocks to have received the outages. Such a large and significant mitigating impact on a community of color is promising.

Other t-test findings at this level of analysis either changed in significance between standard and weighted t-tests, or were of smaller magnitude. However the summation results show larger magnitude differences. In terms of mitigating racial factors, Black-identifying, American-Indian Identifying, and Other utility customers were 29.3%, 27.4%, and 16.5% less likely respectively to receive outages than other threatened groups. Asian customers were 6.3% more likely, and Hispanic customers were 7.9% more likely. Utility customers in poverty were 5.57% more likely to receive outages.

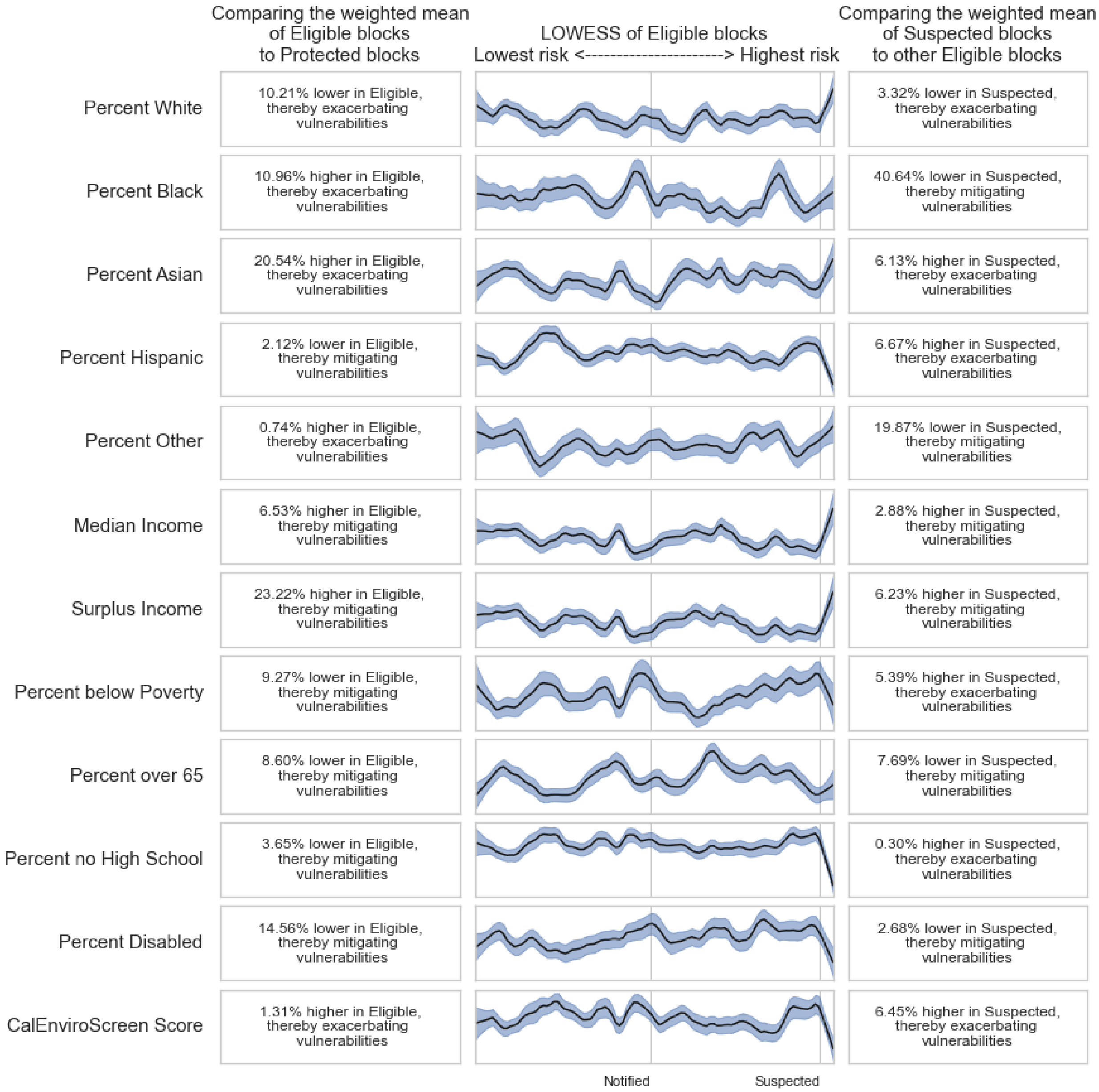


Figure 6.3: Demographic and Environmental Risk across rotating outage planning and implementation levels

The left column of Figure 6.3 examines Eligibility. It compares the population-weighted mean of each demographic or environmental risk value of blocks Eligible for rotating outages to that of blocks Exempt from rotating outages. It notes the relative magnitude, direction, and whether these findings exacerbate or mitigate recognized vulnerabilities. The center column of Figure 6.3 examines Rank order. It displays the LOWESS (Locally weighted scatterplot smoothing) of each demographic or environmental risk value along the rank-ordered list of eligible rotating outage blocks. Each LOWESS in black uses a bandwidth of 0.1 and the blue shading represents the 95% confidence interval. Vertical lines indicate the lowest-risk rotating outage block group that was i) Notified of imminent outages and ii) Suspected of having experienced the rotating outages. The right column of Figure 6.3 examines Experience. It compares the population-weighted mean of each demographic or environmental risk value of blocks Suspected of experiencing the rotating outages to that of all other Eligible blocks. It also notes the relative magnitude, direction, and whether these findings exacerbate or mitigate recognized vulnerabilities. All comparisons were made using weighted t-tests and were significant to a Bonferroni-corrected p-value of 0.0041666, except for ‘Percent no High School’ for Suspected Experienced blocks which was only significant to $p = 0.071$.

6.5 Qualitative procedural justice discussion

In this section, we explore the fairness of rotating outages plans in terms of procedural justice, specifically focusing on transparency and implementation of the plans as intended.

Both the Preliminary and Final Root Cause Analysis Reports for the August 2020 rotating outages document that the rotating outages experienced by PG&E customers on both days significantly exceeded the load shed capacity and duration called for by CAISO. The same report indicates that no other utility overshed load in terms of capacity or duration. Data from Tables 3.1 and 3.2 in the Final Root Cause Analysis Report(“Final Root Cause Analysis Mid-August 2020 Extreme Heat Wave” 2021; “Preliminary Root Cause Analysis: Mid-August 2020 Heat Storm” 2020) indicate that:

- PG&E shed more MW than initiated by CAISO both days
  - 28% more than requested on August 14th
  - 99.5% more than requested on August 15th
- PG&E’s outages lasted longer than called for by CAISO
  - Outages Finished 30 minutes after Stage 3 Emergency canceled on August 14th
  - Outages Finished 67 minutes after Stage 3 Emergency canceled on August 15th

In addition, several reports document that PG&E did not implement their rotating outage plan, but a different load shedding protocol.

California Public Resources Codes § 25700-25705 require all electric utilities in the state to prepare an emergency load curtailment plan designed to “protect public health, safety, and welfare.” [7] In these plans which are revised and reviewed by the California Public Utilities Commission (CPUC) at least every 5 years, utilities propose how to identify priority loads or users when there are ‘sudden and serious shortages’ of electric capacity. Code 25702 explicitly includes provisions for differentiating ‘curtailment of energy consumption by users on the basis of ability to accommodate such curtailments.’

The Final Root Cause Analysis Report states: “Because PG&E received less than 10 minutes’ warning to begin shedding load, it implemented its operating instructions protocol (covered in NERC standard COM-002-4) rather than its rotating outage protocol, for which more than 10 minutes’ advance warning is required. PG&E’s operating instructions protocol required the implementation of manual switching using field personnel, resulting in longer-duration outages because of the need for manual restoration.” [1] Therefore PG&E was unable to implement its emergency protocol that it is legally bound to have specifically for the case of ‘sudden and serious shortages’ during this emergency of sudden and serious shortages of electric capacity. In addition, upon further investigation, the cited NERC standard concerns communications, not load shedding or electricity reliability. Further, the other IOUs - Southern California Edison, and San Diego Gas and Electric - were given the same amount of time to implement rotating outages and were able to implement their curtailment plans as intended.

Because the protocol was not implemented as intended, there is reason to believe that locations other than the rank-ordered list of eligible circuits were shut off, or were shut off in a different order. Using publicly available information we qualitatively compare the locations of the top ten eligible rotating outage block shapefiles, press releases made by PG&E as to what counties were shut off by the rotating outages, and outage records from PowerOutage.US.

News releases from PG&E document that the outages on Friday, August 14th impacted 220,000 customers in "El Dorado, Marin, Napa, San Mateo, and Sonoma" Counties [30]. News releases from PG&E later document that the outages on Saturday, August 15th again impacted 220,000 customers "in portions of the Central Coast and Central Valley, including Monterey, Santa Cruz and San Joaquin counties." [31] The numbers of customers documented in the news reports were 27% and 6% less, respectively for August 14th and 15th, than the numbers documented in CAISO's Final Root Cause Analysis Report [1]. Outage records from PowerOutage.US collaborate these news reports concerning which counties were predominantly affected during these rotating outage events.

However, several of these counties (particularly El Dorado and Sonoma counties) contained no rotating outage block shapefiles that should have been shutoff if the rotating outage plan had been implemented as intended. Further only 18.6% of the 1020 rotating outage circuit shapefiles of the top ten outage blocks were located in these eight counties. The Sacramento Bee noted that "El Dorado County was one of the darkest areas of Northern California Friday night. More than 21,000 in El Dorado Hills, nearly 15,000 in Shingle Springs and 10,000 in Placerville were included in the outages. In all, more than 70,000 customers in the county were affected. About 2,000 were also without power in Yolo County." [32]

Along with short and shared, the third way in which existing rotating outage plans incorporate their version of equity is to diversify the geography of shutoffs. This entails not de-energizing circuits that are right next to each-other in order to limit the distance customers would have to travel to access power if needed. However, the above documentation of shutoffs had very little geographic diversity; the locations of rotating outages were focused in a small number of counties, some in which nearly the entire county was shut off. Even by internally defined measures of equity, the strongly clustered location of the rotating outages indicate further energy injustices.

These disparities in the number of affected customers, the locations of those outages, their geographic clustering, and in-congruence with the plans in place to distribute outages fairly all serve to indicate serious issues in PG&E's implementation of their stated procedures.

In terms of transparency, notice, documentation, and follow-through, we document additional concerns. Of California's three IOUs, PG&E's rotating outage procedure and circuit prioritization is the least accessible and transparent to their customers. For example, SDG&E has a publicly redacted version of their Electric Emergency Plan freely available online. SDG&E also includes the rank-order of outage blocks and a record of past interruptions clearly apparent and always available on their website.

Further general indications of PG&E's lack of concern about these events can be found in other reports published by the utility. The 2020 Joint Annual Report to Shareholders never once mentions the rotating outage events in August 2020 in the 248 page report, however it does include the word "Dividend" 73 times. PG&E's 2021 Corporate Sustainability Report barely mentions rotating outage events in August 2020; only once to reflect on the importance of demand response and once as a scapegoat for their worse annual reliability metrics (SAIDI/SAIFI).

In summary, PG&E was not transparent about their rotating outage plan, their prioritization, or their implementation. There are strong qualitative indications from publicly available information that the IOU did not follow their own emergency load curtailment plan and acted against their own internal definitions of rotating outage equity.

6.6 Heat vulnerability during power outages

The importance of examining disparities in the distribution of rotating outages during this climate emergency lies in the interconnected, compounding risk of extreme heat. Not only are low-income households more likely to reduce their energy consumption to limit financial stress even before power outages [33], they are also more likely to live in less energy efficient [15] and poorly-insulated homes. Further, Hispanic and Black communities are associated with increased annual prevalence of durable medical equipment rentals. Therefore, these communities are more likely to be dependent on electricity-powered medical devices [34]. Other research has documented that these same communities reported the greatest concerns about health during power outages [35]. Higher threat risk combined with lower adaptive capacity [29] and lower disaster preparedness [36] leads to worse health outcomes for vulnerable communities.

The Central Valley - de-energized on August 15th - is known for having some of the largest Hispanic-identifying communities in the state, as shown in Figure 6.1b. It was also one of the hottest areas in PG&E's service territory during the heat-emergency-induced rotating power outages. Spatially average maximum temperature on the affected days displayed in Figure 6.1d shows that large portions of the central valley were above 108 F. The National Weather Service's Heat Index categorizes temperatures such as these as "Dangerous" as detailed further in Figure C.3. The National Ocean and Atmospheric Administration (NOAA) documented temperatures above 104 F in all eight above-identified counties at the times of the outages.

While a Black-identifying individual was 29.3% less likely than the average IOU customer to be in the top ten rotating outage blocks that were de-energized on August 14th and 15th, a Hispanic-identifying individual was 7.8% more likely to be de-energized. These multiple interconnected risks highlight the importance of equity analyses so that the implementation of rotating outages can be brought inline with the California Public Resources Code mandated that "curtailment of energy consumption by users [should be made] on the basis of ability to accommodate such curtailments."[7]

6.7 Equitable and actionable policy suggestions

The Final Root Cause analysis calls for immediate action to update the resource and reliability planning targets to better account for: i) Heat storms and other extreme events resulting from climate change like the ones encountered in both August and September; and ii) A transitioning electricity resource mix to meet the clean energy goals of the state during critical hours of grid need. There are also clear opportunities to incorporate justice at the core of California's climate-emergency response plans.

The California Environmental Protection Agency defines disadvantaged communities, for the purposes of State Bill 535, as census tracts with the highest 25 percent of overall scores in CalEnviroScreen. This designation is used in a number of energy and environmental programs such as directing targeted investments of proceeds from the state's Cap-and-Trade Program to these communities. Figure **??** depicts the proportion of eligible rotating outage blocks suspected to have experienced outages by demi-decile (20 quantiles) of CalEnviroScreen Score. The top 5 demi-deciles compose the top 25% of CalEnviroScreen Scores in PG&E's service territory and would therefore be categorized as 'disadvantaged communities' in California law.

Besides the very highest and very lowest demi-deciles, Figure **??** shows approximately equal distribution of suspected outage experience with increasing CalEnviroScreen score. Actively moving census tracts legally designated as disadvantaged communities from eligible to exempt from rotating outages would incorporate equity into the emergency response plans of all of California's IOUs, align this energy policy with state environmental justice policy, and limit the disproportionate health risks incurred when the most vulnerable communities have their power shut off first.

Moving disadvantaged communities from eligible to exempt can be taken to proactively reduce disproportionate and health risk from future rotating outages. Incorporating temporally and spatially dynamic variables such as extreme temperature, location of wildfires, and dangerous air quality would take active and ongoing consideration to direct outages based on temporally and locationally-specific adaptive capacity.

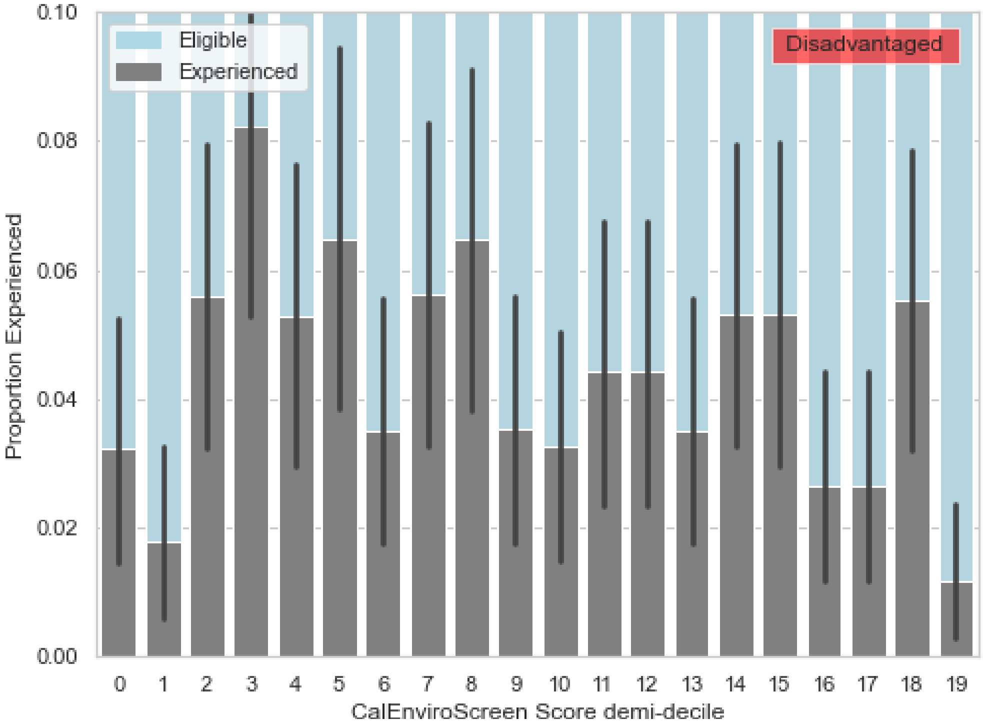


Figure 6.4: Proportion of eligible rotating outage blocks suspected to have experienced outages by demi-decile of CalEnviroScreen Score

6.8 Conclusion

This quantitative distributive justice and qualitative procedural justice analysis finds that these rotating power outages were not short, not shared, not rotated through, not implemented as intended, and not transparently documented. Whether because of heat-waves in California or freezes in Texas, extreme climate events necessitating extreme grid measures will only become more frequent with climate change. Equity therefore needs to be integrated throughout the planning, implementation, and evaluation of rotating outages to not only avoid grid-wide blackouts, but also ensure that the most vulnerable populations in our state are not burdened with disproportionate risk.

Sovacool et al (2016) states: "No matter how noble the intentions of engineers / planners, [or how good the technological design], they have their own inescapable underlying ramifications for justice." [6] If equity is not explicitly taken into account in policy decisions, events will likely exacerbate existing structural inequalities in society and cause detrimental harm to the most vulnerable populations. For example, research on rooftop photovoltaic systems found that incentives that were not specific to low-to-moderate-income households do not improve, and may indeed exacerbate PV adoption inequity [37]. Approaches that are color and income-blind are not sufficient [29].

Analyzing the equity implications of California's rotating outages revealed statistically significant and severe disparities across race, health, and environmental burden. Notions of both distributive and procedural justice were violated in the planning and implementation of shutoffs. With analyses such as this, California now has the opportunity to not leave communities of color in the dark.

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Part III

Conclusion

Chapter 7

Conclusion

Energy justice is a quickly growing area of academic and public interest that aims to ensure equitable access to the benefits and burdens of our energy system and just transition. This dissertation makes important theoretical and practical contributions to the academic literature and produces actionable policy outcomes.

Part I of this dissertation provides the context, theory and methods from which Part II builds.

Chapter 1 provides the largest and most comprehensive, systematic review of energy justice literature to date covering 2,290 papers published between 1983 and 2022. This review build's significantly from Jenkins et al (2021) (which only covered only 155 papers) by using quantitative bibliometric methods that can map the diverse and fast growing literature with methods appropriate to the scale and diversity of publications. We reveal trends in key themes unseen in more narrow reviews and highlight the under-recognized contribution of energy poverty as an earlier precursor to energy justice.

Chapter 2 investigates the philosophical and ethical roots of energy justice revealing key disconnects and opportunities for a more grounded theory base in this emerging field. This chapter builds on Jenkins et al. (2021) and Sovacool et al (2016) which are the first and fifth most cited energy justice publications in the review from chapter 1, and which present the two most common theory frameworks in the field. However placed in the context of broader justice debates and approaches from other social theory and political philosophy disciplines, we find them to be lacking. The comprehensive aims of energy justice will fail to take shape if the field continues to neglect the potential contributions that justice theory can make to energy justice.

Chapter 3 reviews the diverse quantitative approaches used in distributive energy justice research. It first reviews the philosophical basis for distributive energy justice claims, and then uses this philosophical basis to formalize categories of quantitative methods for operationalizing distributive energy justice comparisons. In particular, we make a distinction between equality and equity, ask what functional forms of equality and equity are appropriate, and ask what does making the different functional forms explicit imply for future energy justice research.

Part II applies the above theory and methods to three energy justice concerns at the intersection fair access to reliabile electricity.

Chapter 4 uses mixed methods to examine how gender mediates access to the benefits for off-grid solar in rural Tanzania. Women and low-income households experience a disproportionate burden of energy poverty. Despite this, many electrification plans insufficiently address gender and low-income households. Off-grid solar has and will continue to play a role in expanding access to electricity in rural Sub-Saharan Africa; however, off-grid solar is rarely examined across genders. This research draw on quantitative surveys and qualitative interviews from a case study in rural Tanzania to investigate the energy justice implications of off-grid solar. This chapter ask how the distributional benefits of solar are mediated by gender and class, filling a key gap in the literature of off-grid solar's impact. Little evidence of gender differentiation is found, suggesting equality within off-grid solar usage, but not equity. Solar remains out of reach for low-income households. In this case study, off-grid solar is used both as a primary source for low-and-middle-income households, and as a back-up source for middle-and higher-income households. Solar is found to be under-used as a means of income generation and that payment schemes may not be the key to achieving energy justice. Further work is needed to ensure that women and low-income households have not only equal, but equitable access to the benefits of off-grid solar.

In similar communities to Chapter 4, **Chapter 5** moves from examining solely off-grid solar, to measuring how the reliability of electricity access varies across different electricity access solutions. The United Nations identifies ensuring "access to affordable, reliable, sustainable and modern energy for all" as one of its Sustainable Development Goals for 2030. This chapter focuses on the comparatively under-investigated question of reliability within the broader goal. This chapter empirically studies experienced household electricity reliability using common frameworks in key countries such as Tanzania, Kenya, and India. Datasets represent a diverse set of technologies including solar home systems (SHS), solar pico-grids, and national electricity grids. First, the prevailing reliability metrics - SAIDI and SAIFI – are measured for all datasets. Informed by critical assessments, this chapter then proposes a suite of new metrics that facilitate improved reliability comparisons by considering the reasons, timing, and fairness of outage distribution. Analyses using the proposed metrics reveal key policy implications for addressing energy poverty in the Global South. Acknowledging that the systems studied provide different capacity, affordability, and carbon footprints, on average, SHS provided comparable hours of lighting to local grid connections, however SHS outages were less equally distributed than those from other sources. In addition, calculations of grid reliability were highly sensitive to measurement techniques and assumptions used, necessitating high resolution data for policy decisions. Finally, economically driven outages conspicuous in pre-paid SHS systems (i.e., disconnections for non-payment) composed a significant portion of experienced unreliability. These findings quantify the important contribution of demand-side affordability to experienced household reliability, thereby allowing for a comprehensive understanding of the reliability of SDG 7.

Still examining the fairness of electricity reliability, **Chapter 6** moves from rural Tanzania, to Northern California. This chapter examines the extent to which communities across California were differentially affected by the heat-wave-provoked rotating power outages in Fall 2020 viewed through lenses of distributive and procedural justice. We find statistically significant and severe energy injustices across racial and ethnic lines. Across different decision-making levels of rotating outage planning and implementation we find higher proportions of the population self-identifying as Asian, Hispanic, and Black. While eligibility speaks more to injustices surrounding population dynamics and access to essential infrastructure, notification and suspected experience reveal energy inequities unexplained by other compounding factors, and which place disproportionate burdens on some communities of color. These types of outages are meant to be ‘short and shared,’ so while mitigating factors such as income and health are also observed, strong racial signatures are of concern. These outages are implemented by regulated agencies acting in the general public’s interest to avoid grid-wide brownouts, therefore, there are immediate policy implications to ensure equitable decision-making during future climate disasters.

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’ will require significant efforts by all stakeholders. This dissertation applies theories of just energy systems to actionable energy justice concerns so that some day we can ensure fair access to reliable electricity for all.

Appendix A

Publication and Contribution List

Published

- 10. **Ferrall, I.,** Callaway, D., Kammen, D.M., 2022. Measuring the reliability of SDG 7: the reasons, timing, and fairness of outage distribution for household electricity access solutions. Environmental Research Communications [1]
- 9. Patel, S.N., **Ferrall, I.,** Khaingad, B., Kammen, D.M., 2022. Sustainable and socially resilient minigrid franchise model for an urban informal settlement in Kenya. Economics of Energy and Environmental Policy 11. https://doi.org/10.5547/2160-5890.11.1.spat [2] *Pre-print available on Sustainable Development Goals Online from Taylor & Francis. https://www.taylorfrancis.com/cw/sustainable-socially-resilient-minigrid-franchise-model-urban-informal-settlement-kenya-serena-patel-isa-ferrall-byrones-khaingad-daniel-kammen/10.4324/3d1c8604-8b9f-4285-9f19-9de1884df81e?context=sdgo. In collaboration with the Kibera Town Center at the Human Needs Project, Nairobi, Kenya*
- 8. **Ferrall, I.,** Gill-Wiehl, A., Patel, S., Miles, S., Yu, H., Wu, J., Kammen, D.M., 2021a. Community energy infrastructure: Point-of-service clean energy to serve the food/water/health nexus. in: Proceedings of Applied Energy Symposium: MIT A+B. Energy Proceedings, Volume 15: Technology Innovation to Accelerate Energy Transitions. Presented at the MIT A+B Applied Energy Symposium (MITAB), Cambridge, Massachusetts. https://www.energy-proceedings.org/community-energy-infrastructure-point-of-service-clean-energy-to-serve-the-food-water-health-nexus/ [3] *In collaboration with OffGridBox. Won Best Paper Award.*
- 7. **Ferrall, I.,** Heinemann, G., von Hirschhausen, C., Kammen, D.M., 2021b. The Role of Political Economy in Energy Access: Public and Private Off-Grid Electrification in Tanzania. Energies 14, 3173. https://doi.org/10.3390/en14113173 [4] *In collaboration with Workgroup for Infrastructure Policy, Technische Universität Berlin*

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Submitted for publication:

- Gill-Wiehl, A., **Ferrall, I.,** Kammen, D.M., 2022. Equal goods, but inequitable capabilities? A gender-differentiated study of off-grid solar energy in rural Tanzania
- Gill-Wiehl, A., **Ferrall, I.,** Patel, S., Miles, S., Wu, J., Newman, A., Kammen, D.M., 2022. Containerized, renewable energy for use cases at the food/water/health nexus in Rwanda
- Gill-Wiehl, A., **Ferrall, I.,** Kammen, D.M., 2022. A fraying thread? A gender-differentiated study of equality and equity in off-grid solar usage in rural Tanzania. Chapter in Renewable Energy Transformation or Energy Injustice? Off-grid solar electrification in Africa (in press)

- Finnerty, C., **Ferrall, I.,** 2020. A Teaching Guide for Development Engineering. Chapter in Introduction to Development Engineering : A Framework with Applications from the Field. Edited by Madon and Gadgil, forthcoming Springer textbook

In Prep:

- **Ferrall, I.,** Sunter, D.A., Leaving communities of color in the dark. Rotating outages in California create energy and social injustices. In collaboration with the California Public Utilities Commission
- **Ferrall, I.,** Sunter, D.A., Kammen, D.M., Data mining for innovation in next generation solar technologies
- Adkins, J., Warren, R., Berkouwer, S., **Ferrall, I.,** Klugman, N., Dis-aggregating policy indices reveals reliability and voltage inequality in urban Africa. In collaboration with nLine
- Carvallo, J.P., **Ferrall, I.,** Kammen, D.M., Opperman, J., Capacity expansion modeling for Uganda for high renewables futures. In collaboration with World Wildlife Fund and The Nature Conservancy
- Martin, A., Sareen, S., Kammen, D.M., Mulvaney, D., Meckling, J., Elkin, E., Stock, R., Girard, B., **Ferrall, I.,** Miles, S., Governance for solar transitions: Mapping the requisite interventions for rapid climate mitigation and just transitions in solar photovoltaic value chains

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Appendix B

Chapter 5 Appendix

B.1 Data Sources and Scope

The data sources below are described first in order of system size (from smallest to largest). Within each system size, data sources are organized by location starting with Tanzania, then Kenya, then India.

Solar-home-systems - Tanzania

- Location of systems: 16 regions across Tanzania
- Time frame of data: mid-2015 to mid-2018
- Size of sample: non-random sample of 417 solar-home-systems
- Size of systems: 30 – 120 Wh
- Collaborating Organization: Off-Grid Electric Ltd. (OGE, now Zola Electric)

Off-Grid Electric Ltd. (OGE, now Zola Electric http://zolaelectric.com/) is an energy services company that provides home energy solutions based on solar and storage technologies and PAYGo micro-financing mechanisms. At the end of 2017, OGE had over 100,000 systems in Tanzania and with growing markets in Rwanda and Cote d'Ivoire. Primary system data was collected from their solar-plus-storage kits ranging from 30Wh to 120Wh with appliances such as lighting, phone charging, and DC televisions. For example, a 120Wh lithium-ion battery kit included 50W solar panel, a big lamp, three small lamps, a tube lamp, a USB phone charging kit, a radio, a large DC TV and a USB solar torch. The SHS analyzed in this study were leased using an energy-as-a-service model – where the SHS company retains ownership of the system and is responsible for repairing or replacing any poorly functioning units. In addition, the systems relied on high-quality lithium-ion batteries with expected lifetimes exceeding 5 years. Most of the systems were installed for 1-2 years at the time of data sampling. Therefore, battery degradation was not apparent in the SHS studied nor the responsibility of households.

The authors collected and summarized the primary system data to report outage events (for an average 61 days/system) between mid-2015 to mid-2018 for a non-random sample of 417 SHS installed across 16 regions of Tanzania. Most of the data was recorded during 2016. 109 of the 120 Wh SHS were installed in primary schools and the remaining 308 SHS (ranging 30-120 Wh) were installed in residential households. All the SHS were based in Tanzania and were installed in either residential households or schools. Each SHS was programmed to collect and record information relevant to the state of the system on a local memory chip which was later manually uploaded to a database server. The time-series data of outages per meter includes the i) cause of the outage, ii) a timestamp for when users are no longer able to access electricity from their system, as well as iii) a timestamp for when their access returns.

Solar-pico-grid - India

- Location of systems: Uttar Pradesh
- Time frame of data: January 2016 - December 2016
- Size of sample: meters in 43 households across 7 pico-grids
- Size of systems: 30 W per household
- Collaborating Organization: Numminen et al. (2018). Summarized and reprinted with permission https://doi.org/10.1016/j.seta.2018.08.005

Numminen et al. reported the power availability and reliability of seven low-power direct current (DC) solar-battery pico-grids (SPG) in villages in rural northern India. Each grid connected 5-7 households (average of seven individuals/household) in a village (population 400-800). The SPG supplied basic electricity services (lighting and mobile phone charging) 24/7 but was limited to 30 W per connection. The solar-pico-grid data was measured at household meters between January 2016 - December 2016 in Uttar Pradesh, India. In all forty-three households, energy meters functioned in pre-paid mode with dynamic energy pricing and recorded performance data on ten-minute intervals. Outages were assigned by the lack of measurement values during a ten-minute interval. Additional information is available in the journal article and supporting documentation of Numminen et al. (2018).

Grid – Tanzania (1)

- Location of systems: Dar es Salaam
- Time frame of data: 2017 report (representing 2015-2016) and 2018 report (representing 2016-2017)

- Size of sample: reported by utility
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Doing Business Survey (World Bank, 2018b)

The World Bank's Doing Business Survey annually collects an array of policy and process metrics relevant to starting and operating small and medium enterprises in 190 countries. Annual SAIDI and SAIFI values are requested from the distribution utility companies and national regulators in the largest business city of each economy. For Tanzania, this is Dar es Salaam. These data points are denoted as 'Self-reported' or 'from the utility' because the utility reports its own reliability. Available at https://www.doingbusiness.org/content/dam/doingBusiness/excel/Historical-data—complete-data-with-scores.xlsx

Grid – Tanzania (2)

- Location of systems: Country-wide; Arusha; Dar es Salaam
- Time frame of data: 2013
- Size of sample: firm-level surveys. Country wide [485 firms], Arusha [80 firms], Dar es Salaam [250 firms]
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Enterprise Survey (World Bank, 2018a)

The World Bank's Enterprise Survey is a firm-level, representative sample of an economy's private sector in 139 countries conducted every 4-5 years. Because businesses report their experienced reliability, this data is denoted as 'from Businesses'. Questions in the survey ask about the number of outages in the past month and their typical duration in hours. ("Enterprise Survey Methodology," n.d.) From this information, both SAIDI and SAIFI can be approximated for the country and for specific regions following Taneja (2017). Available via https://www.enterprisesurveys.org/Custom-Query

Grid – Tanzania (3)

- Location of systems: Dar es Salaam
- Time frame of data: January 2017 to May 2018
- Size of sample: 25 sensors
- Size of systems: country-wide grid
- Collaborating Organization: Electricity Supply Monitoring Initiative (ESMI)

The Electricity Supply Monitoring Initiative (ESMI, n.d.), implemented by The Energy Change Lab, provides an additional secondary data source for the electricity grid in Tanzania through its real-time, open-source database on supply interruptions and voltage levels at consumer locations (households and commercial). At twenty-five locations in Dar es Salaam, Tanzania voltage was recorded by the minute and relayed to a central server. The pilot ran from January 2017 to May 2018. Available via http://watchyourpower.org/esmi_beyond_india.php

Grid – Kenya (1)

- Location of systems: greater Nairobi area
- Time frame of data: June 2017 – June 2018
- Size of sample: seven 11 kV feeders
- Size of systems: country-wide grid
- Collaborating Organization: Kenya Power and Lighting Company (KPLC), Institute of Energy Studies and Research

KPLC measured voltage and load on seven 11 kV feeders in the greater Nairobi area between July 2017 and June 2018 on a 15-minute interval. In alignment with the other data sources, the voltage is used to characterize outages. When voltage on any phase was zero or outside of the +/- 10% nominal voltage window set by the Kenya Grid Code (https://www.kplc.co.ke/img/full/wm9o9bvTXEvC_Kenya%20Grid%20Code.pdf), the full fifteen-minutes are categorized as an outage. The data was made available thanks to the support of the Kenya Power and Lighting Company's Institute of Energy Studies and Research, with support from Charles Ndungu and Patrick Mwangi Karimi.

Grid – Kenya (2)

- Location of systems: greater Nairobi area
- Time frame of data: June 2016 to July 2018
- Size of sample: 323 feeders
- Size of systems: country-wide grid
- Collaborating Organization: Kenya Power and Lighting Company (KPLC), Institute of Energy Studies and Research

KPLC recorded the monthly counts of outage incidents on 323 feeders across the greater Nairobi area over the period of June 2016 to July 2018. We analyzed this data based on the methods detailed in Taneja (2017). The data was made available thanks to the support of the Kenya Power and Lighting Company's Institute of Energy Studies and Research, with support from Charles Ndungu and Patrick Mwangi Karimi.

Grid – Kenya (3)

- Location of systems: Nairobi
- Time frame of data: 2017 report (representing 2015-2016) and 2018 report (representing 2016-2017)
- Size of sample: reported by utility
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Doing Business Survey (World Bank, 2018b)

The World Bank's Doing Business Survey annually collects an array of policy and process metrics relevant to starting and operating small and medium enterprises in 190 countries. Annual SAIDI and SAIFI values are requested from the distribution utility companies and national regulators in the largest business city of each economy. For Kenya this is, Nairobi. These data points are denoted as 'Self-reported' or 'from the utility' because the utility reports its own reliability. Available at https://www.doingbusiness.org/content/dam/doingBusiness/excel/Historical-data—complete-data-with-scores.xlsx

Grid – Kenya (4)

- Location of systems: Country-wide; Nairobi
- Time frame of data: 2018
- Size of sample: firm-level surveys. Country wide [839 firms], Nairobi [249 firms]
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Enterprise Survey (World Bank, 2018a)

The World Bank's Enterprise Survey is a firm-level, representative sample of an economy's private sector in 139 countries conducted every 4-5 years. Because businesses report their experienced reliability, this data is denoted as 'from Businesses'. Questions in the survey ask about the number of outages in the past month and their typical duration in hours. ("Enterprise Survey Methodology," n.d.) From this information, both SAIDI and SAIFI can be approximated for the country and for specific regions following Taneja (2017). Available via https://www.enterprisesurveys.org/Custom-Query

Grid – Kenya (5)

- Location of systems: Nairobi
- Time frame of data: November 2017 to October 2018
- Size of sample: 59 sensors
- Size of systems: country-wide grid
- Collaborating Organization: Electricity Supply Monitoring Initiative (ESMI)

ESMI, implemented by The ESMI Kenya Initiative, provides an additional secondary data source for the electricity grid in Kenya through its real-time, open-source database on supply interruptions and voltage levels at residential and commercial locations. At fifty-nine locations in Nairobi voltage was recorded by the minute and relayed to a central server. The pilot ran from November 2017 to October 2018. Available via http://watchyourpower.org/esmi_beyond_india.php or request to mmwangi@eedadvisory.com

Grid – India (1)

- Location of systems: Country-wide
- Time frame of data: 2017 report (representing 2015-2016) and 2018 report (representing 2016-2017)
- Size of sample: reported by utility
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Doing Business Survey (World Bank, 2018b)

The World Bank's Doing Business Survey annually collects an array of policy and process metrics relevant to starting and operating small and medium enterprises in 190 countries. Annual SAIDI and SAIFI values are requested from the distribution utility companies and national regulators in the largest business city of each economy. For India this is Delhi or Mumbai. These data points are denoted as 'Self-reported' or 'from the utility' because the utility reports its own reliability. Available at https://www.doingbusiness.org/content/dam/doingBusiness/excel/Historical-data—complete-data-with-scores.xlsx

Grid – India (2)

- Location of systems: Country-wide; Uttar Pradesh
- Time frame of data: 2014

- Size of sample: firm-level surveys. Country wide [5,921 firms], Uttar Pradesh [454 firms]
- Size of systems: country-wide grid
- Collaborating Organization: World Bank Enterprise Survey (World Bank, 2018a)

The World Bank's Enterprise Survey is a firm-level, representative sample of an economy's private sector in 139 countries conducted every 4-5 years. Because businesses report their experienced reliability, this data is denoted as 'from Businesses'. Questions in the survey ask about the number of outages in the past month and their typical duration in hours. ("Enterprise Survey Methodology," n.d.) From this information, both SAIDI and SAIFI can be approximated for the country and for specific regions following Taneja (2017). Available via https://www.enterprisesurveys.org/Custom-Query

Grid – India (3)

- Location of systems: India
- Time frame of data: September 2015 – December 2019
- Size of sample: 437 sensors across India, 18 in Uttar Pradesh
- Size of systems: country-wide grid
- Collaborating Organization: Electricity Supply Monitoring Initiative (ESMI)

The ESMI sensors in Uttar Pradesh, India, and others across the country measured and reported data at residential and commercial locations from September 2015 up through the writing of this article. Data is available via their website at http://watchyourpower.org/index.php or on the Harvard Dataverse at https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/CLLZZM. (Prayas, Energy Group, 2019)

B.2 Figure 5.2 expanded details

Figure 5.2 Raw comparisons of SAIDI and SAIFI across all datasets in Tanzania, Kenya, and India and sub-regions. Decentralized systems are noted in warm colors (orange and pink) while centralized grid systems are in cool colors (greens and blues). Marker shape designates the data collection method. Horizontal dashed lines mark the threshold between Tiers 4 and 5 in the ESMAP Multi-tier framework. All values are taken from the closest period to 2016, are scaled by data availability to represent one full year and have momentary and MED cut-offs applied.

		Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Availability (Duration)	Hours per day		Min 4	Min 4	Min 8	Min 16	Min 23
	Hours per evening		Min 1	Min 2	Min 3	Min 4	Min 4
Reliability						Max 14 disruptions per week	Max 3 per week of total duration $\leq$ 2 hrs

Table B.1: ESMAP Multi-Tier Framework thresholds relevant to reliability

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
SAIDI Equivalent (hours/year/household)		Max 7300	Max 7300	Max 5840	Max 2920	Max 365
SAIFI Equivalent (count/year/household)					Max 728	Max 156 of total duration $\leq$ 2 hrs

Table B.2: SAIDI and SAIFI Equivalents for ESMAP Multi-Tier Framework thresholds relevant to reliability

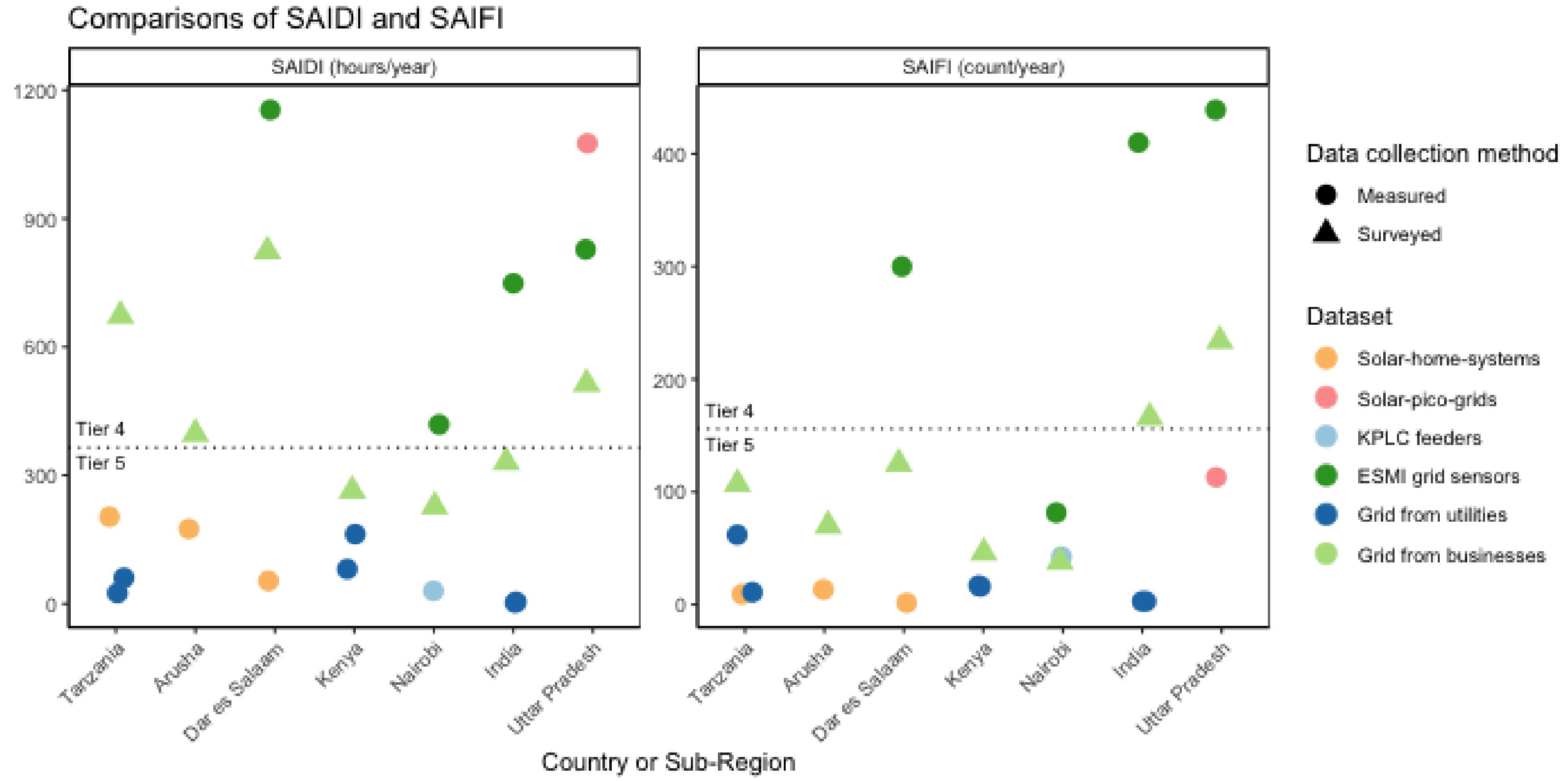
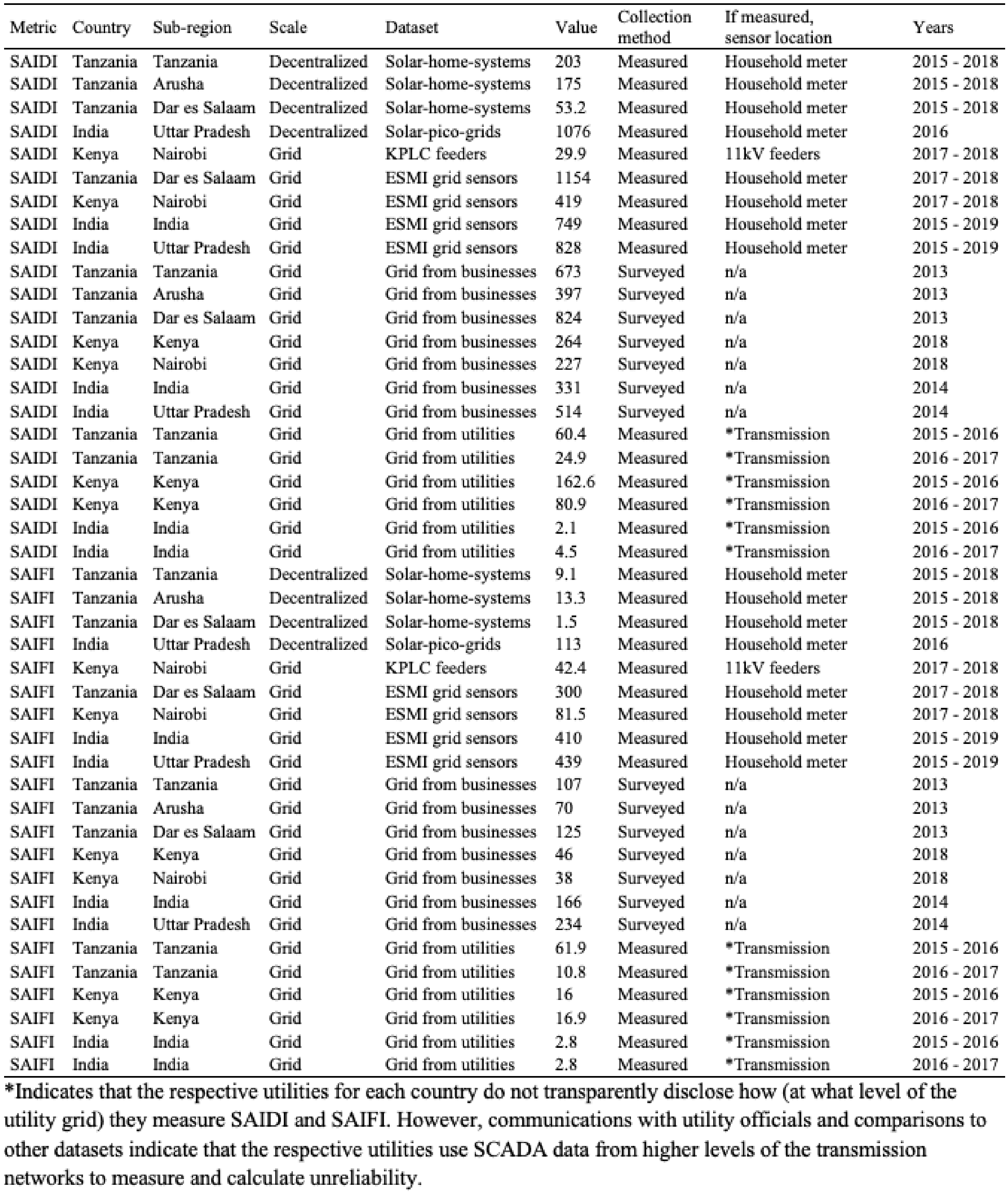


Figure B.1: Status quo comparisons of SAIDI and SAIFI across all datasets in Tanzania, Kenya, and India and sub-regions



Metric	Country	Sub-region	Scale	Dataset	Value	Collection method	If measured, sensor location	Years
SAIDI	Tanzania	Tanzania	Decentralized	Solar-home-systems	203	Measured	Household meter	2015 - 2018
SAIDI	Tanzania	Arusha	Decentralized	Solar-home-systems	175	Measured	Household meter	2015 - 2018
SAIDI	Tanzania	Dar es Salaam	Decentralized	Solar-home-systems	53.2	Measured	Household meter	2015 - 2018
SAIDI	India	Uttar Pradesh	Decentralized	Solar-pico-grids	1076	Measured	Household meter	2016
SAIDI	Kenya	Nairobi	Grid	KPLC feeders	29.9	Measured	11kV feeders	2017 - 2018
SAIDI	Tanzania	Dar es Salaam	Grid	ESMI grid sensors	1154	Measured	Household meter	2017 - 2018
SAIDI	Kenya	Nairobi	Grid	ESMI grid sensors	419	Measured	Household meter	2017 - 2018
SAIDI	India	India	Grid	ESMI grid sensors	749	Measured	Household meter	2015 - 2019
SAIDI	India	Uttar Pradesh	Grid	ESMI grid sensors	828	Measured	Household meter	2015 - 2019
SAIDI	Tanzania	Tanzania	Grid	Grid from businesses	673	Surveyed	n/a	2013
SAIDI	Tanzania	Arusha	Grid	Grid from businesses	397	Surveyed	n/a	2013
SAIDI	Tanzania	Dar es Salaam	Grid	Grid from businesses	824	Surveyed	n/a	2013
SAIDI	Kenya	Kenya	Grid	Grid from businesses	264	Surveyed	n/a	2018
SAIDI	Kenya	Nairobi	Grid	Grid from businesses	227	Surveyed	n/a	2018
SAIDI	India	India	Grid	Grid from businesses	331	Surveyed	n/a	2014
SAIDI	India	Uttar Pradesh	Grid	Grid from businesses	514	Surveyed	n/a	2014
SAIDI	Tanzania	Tanzania	Grid	Grid from utilities	60.4	Measured	*Transmission	2015 - 2016
SAIDI	Tanzania	Tanzania	Grid	Grid from utilities	24.9	Measured	*Transmission	2016 - 2017
SAIDI	Kenya	Kenya	Grid	Grid from utilities	162.6	Measured	*Transmission	2015 - 2016
SAIDI	Kenya	Kenya	Grid	Grid from utilities	80.9	Measured	*Transmission	2016 - 2017
SAIDI	India	India	Grid	Grid from utilities	2.1	Measured	*Transmission	2015 - 2016
SAIDI	India	India	Grid	Grid from utilities	4.5	Measured	*Transmission	2016 - 2017
SAIFI	Tanzania	Tanzania	Decentralized	Solar-home-systems	9.1	Measured	Household meter	2015 - 2018
SAIFI	Tanzania	Arusha	Decentralized	Solar-home-systems	13.3	Measured	Household meter	2015 - 2018
SAIFI	Tanzania	Dar es Salaam	Decentralized	Solar-home-systems	1.5	Measured	Household meter	2015 - 2018
SAIFI	India	Uttar Pradesh	Decentralized	Solar-pico-grids	113	Measured	Household meter	2016
SAIFI	Kenya	Nairobi	Grid	KPLC feeders	42.4	Measured	11kV feeders	2017 - 2018
SAIFI	Tanzania	Dar es Salaam	Grid	ESMI grid sensors	300	Measured	Household meter	2017 - 2018
SAIFI	Kenya	Nairobi	Grid	ESMI grid sensors	81.5	Measured	Household meter	2017 - 2018
SAIFI	India	India	Grid	ESMI grid sensors	410	Measured	Household meter	2015 - 2019
SAIFI	India	Uttar Pradesh	Grid	ESMI grid sensors	439	Measured	Household meter	2015 - 2019
SAIFI	Tanzania	Tanzania	Grid	Grid from businesses	107	Surveyed	n/a	2013
SAIFI	Tanzania	Arusha	Grid	Grid from businesses	70	Surveyed	n/a	2013
SAIFI	Tanzania	Dar es Salaam	Grid	Grid from businesses	125	Surveyed	n/a	2013
SAIFI	Kenya	Kenya	Grid	Grid from businesses	46	Surveyed	n/a	2018
SAIFI	Kenya	Nairobi	Grid	Grid from businesses	38	Surveyed	n/a	2018
SAIFI	India	India	Grid	Grid from businesses	166	Surveyed	n/a	2014
SAIFI	India	Uttar Pradesh	Grid	Grid from businesses	234	Surveyed	n/a	2014
SAIFI	Tanzania	Tanzania	Grid	Grid from utilities	61.9	Measured	*Transmission	2015 - 2016
SAIFI	Tanzania	Tanzania	Grid	Grid from utilities	10.8	Measured	*Transmission	2016 - 2017
SAIFI	Kenya	Kenya	Grid	Grid from utilities	16	Measured	*Transmission	2015 - 2016
SAIFI	Kenya	Kenya	Grid	Grid from utilities	16.9	Measured	*Transmission	2016 - 2017
SAIFI	India	India	Grid	Grid from utilities	2.8	Measured	*Transmission	2015 - 2016
SAIFI	India	India	Grid	Grid from utilities	2.8	Measured	*Transmission	2016 - 2017

*Indicates that the respective utilities for each country do not transparently disclose how (at what level of the utility grid) they measure SAIDI and SAIFI. However, communications with utility officials and comparisons to other datasets indicate that the respective utilities use SCADA data from higher levels of the transmission networks to measure and calculate unreliability.

Figure B.2: Supporting data for Figure 5.2

B.3 SAIDI and SAIFI calculation method

The analysis methods used throughout this paper build directly from the IEEE Guide for Electric Power Distribution Reliability Indices (IEEE 1366). In particular, we follow the standard to measure the SAIDI and SAIFI values in Table 3. The additional assumptions needed to apply the standard to our novel decentralized system datasets are detailed in SI.3. SAIDI and SAIFI calculation assumptions.

We will begin by summarizing the following relevant portions of the IEEE Guide for Electric Power Distribution Reliability Indices, 2012. IEEE Std 1366-2012 Revis. IEEE Std 1366-2003 1–43. https://doi.org/10.1109/IEEESTD.2012.6209381

Section 3.2 Sustained Interruption indices

3.2.1 SAIFI: System Average Interruption Frequency Index

The System Average Interruption Frequency Index (SAIFI) indicates how often the average customer experiences a sustained interruption over a predefined period of time. Mathematically, this is:.

$$SAIFI = \frac{\sum Total\ Number\ of\ Customers\ Interrupted}{Total\ Number\ of\ Customers\ Served} \tag{B.1}$$

To calculate the index, use the following:

$$SAIFI = \frac{\sum N_i}{N_T} = \frac{CI}{N_T} \tag{B.2}$$

Where:
CI = Customers interrupted
N_i = Number of interrupted customers for each sustained interruption event during the reporting period
N_T = Total number of customers served for the area

3.2.2 SAIDI: System Average Interruption Duration Index

The System Average Interruption Duration Index (SAIDI) indicates the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in minutes or hours of interruption. Mathematically, this is:

$$SAIDI = \frac{\sum Customer\ Minutes\ of\ Interruption}{Total\ Number\ of\ Customers\ Served} \tag{B.3}$$

To calculate the index, use the following:

$$SAIDI = \frac{\sum r_i N_i}{N_T} = \frac{CMI}{N_T} \tag{B.4}$$

Where:
CMI = Customer minutes of interruption
r_i = Restoration time for each interruption event

Section 3.5 Major Event Day classification

The Beta Method is used to identify Major Event Days (MED), provided that the natural log transformation of the data results closely resembles a Gaussian (normal) distribution. Its purpose is to allow major events to be studied separately from daily operation, and in the process, to better reveal trends in daily operation that would be hidden by the large statistical effect of major events.

A MED is a day in which the daily system SAIDI exceeds a threshold value, T_{MED}. The SAIDI index is used as the basis of this definition since it leads to consistent results regardless of utility size, and because SAIDI is a good indicator of operational and design stress. Even though SAIDI is used to determine the MEDs, all indices should be calculated based on removal of the identified days.

In calculating daily system SAIDI, any interruption that spans multiple days is accrued to the day on which the interruption begins.

The following is a mathematical summarization of the T_{MED} identification process. This is further detailed in Section 3.5 and Annex B of the standard. T_{MED} was calculated for each dataset independently.

1. Find the natural log of daily SAIDI

   $$x_i = ln(SAIDI_i) \tag{B.5}$$

   where $SAIDI_i$ represents the dataset's SAIDI for each day for up to five years prior, excluding days that did not have any interruptions

2. Find α(Alpha), the log-average

   $$\alpha = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{1}{N}\sum_{i=1}^{N} ln(SAIDI_i) \tag{B.6}$$

   where $N_{max} = present$ and $N_{min} = N_{max} - upto5years$

3. Find β (Beta), the log-standard deviation

   $$\beta = \sqrt{\frac{\sum(x_i - a)^2}{N}} = \sqrt{\frac{\sum(ln(SAIDI_i) - a)^2}{N}} \tag{B.7}$$

4. Compute T_{MED} using

   $$T_{MED} = e^{(\alpha+2.5\beta)} \tag{B.8}$$

Any day with daily SAIDI greater than the threshold value T_{MED} that occurs during the subsequent reporting period is classified as a MED. Activities that occur on days classified as MEDs should be separately analyzed and reported.

Specific application of this method to an example dataset can be found in the Supplemental Material of "Measuring the reliability of SDG 7: the reasons, timing, and fairness of outage distribution for household electricity access solutions" published in Environmental Research Communications in 2022.

Appendix C

Chapter 6 Appendix

C.1 Authors' note

At the time of publication, there were a total of seven days in August and September 2020, and July 2021 where CAISO raised Stage 2 or 3 alerts directing the IOUs to respectively threaten or implement forced rolling power outages. Our 'notified of imminent outages' and 'suspected to have experienced outages' results are based on information from two of these six days in PG&E's service territory which we obtained from PG&E's public webpage on Rotating Outage Status www.pge.com/rotatingoutages/. However, the later removal of formerly public data limited our ability to apply the analysis to the remaining days across PG&E's service territory. Limited geospatial information prevented our extension of this analysis to the other IOUs in California. The authors made multiple formal requests to all three IOUs for the remaining information which were either rejected or ignored. Despite much of this data having previously been publicly available, it still has not been made accessible to the authors. As to not delay publication of the dramatic disparities evidenced by the days analyzed, the authors have not included the other four days and other service territories for which data was not available. If and when this data is made available, the authors would repeat this analysis and provide an amendment to this article.

Data type	*Resolution*	*Yielded*	*Census Table #*
Race and ethnicity	Block group	Percentages and summations of the population of different races and ethnicities	B03002
Age	Block group	Percent of the population over 65	B01001
Income	Block group	Median household income pre-tax	B19013
Poverty	Block group	Percent of the population in poverty, and percent two-times the poverty line	C17002
Education	Block group	Percent of the population over the age of 25 who had not received a high-school diploma or equivalent	B15003
Disability	Tract	Percent of the population with a disability	B18101

C.2 Data Sources

Rotating outages

The shapefiles of rotating outage blocks across PG&E's service territory and the timetables of threatened outage blocks were gathered through PG&E's public web portal at www.pge.com/rotatingoutages.

Demographics

We sourced the majority of our demographic data via the US Census Bureau's data portal at https://data.census.gov/cedsci/. Using '2019 American Community Survey 5-year Estimates Detailed Tables' at a census block resolution, we sourced information on:

- The American Community Survey (ACS) is an ongoing survey that provides data every year – giving communities the current information they need to plan investments and services. The ACS covers a broad range of topics about social, economic, demographic, and housing characteristics of the U.S. population.
- The 5-year estimates from the ACS are "period" estimates that represent data collected over a period of time. The primary advantage of using multiyear estimates is the increased statistical reliability of the data for less populated areas and small population subgroups

- We use the 2019 data from the 2015-2019 ACS 5-Year estimates, as 2019 is the most recent survey fully available and is closest to the demographics of California when these events occurred.
- Race and ethnicity percentages for each census block group were defined by first dividing the population self-identifying their ethnicity as Hispanic by the total population to arrive at a percent Hispanic for each census block group. Then, for each major race category, the population identifying their ethnicity as non-Hispanic and their race as White, Asian, and Black respectively was divided by the total population to arrive at percent non-Hispanic White, percent non-Hispanic Asian, and percent non-Hispanic Black. The difference between 100% and the sum of percent Hispanic, White, Asian, and Black was categorized as percent 'other'.
- Information for surplus income was sourced from the Living Wage Calculator for California at https://livingwage.mit.edu/states/06/locations. We defined surplus income as the difference between median household income and required annual income. Median household income at the census block level was sourced from the Census Bureau as noted above. Required annual income before taxes was found for each county at the median household size for the state of California in the 2018 American Community Survey 5-year Estimates Detailed Tables (2 workers and 1 child).
- Demographic data at the census block level was assigned to rotating outage blocks using a weighted average of area coverage, thereby assuming that demographics are evenly spread across census block groups.

Environmental Risk

We quantify environmental risk at the census tract level through CalEnviroScreen scores available at https://oehha.ca.gov/calenviroscreen/maps-data/download-data. CalEnviroScreen is a mapping tool that helps identify California communities that are most affected by many sources of pollution, and where people are often especially vulnerable to pollution's effects. CalEnviroScreen uses environmental, health, and socioeconomic information to produce scores for every census tract in the state. The scores are mapped so that different communities can be compared. An area with a high score is one that experiences a much higher pollution burden than areas with low scores.

Weather

Daily temperature was sourced through NOAA's National Center for Environmental Information, Daily Summaries Mapping Tool at https://gis.ncdc.noaa.gov/

maps/ncei/summaries/daily. Daily Maximum Temperature (MxTp) was gathered for the selected days at over 500 geolocated stations across California and was then assigned to rotating outage blocks using the nearest neighbor to the centroid of each block. Daily air quality was sourced through the EPA's Air Now and Air Quality System, Outdoor Air Quality Data, Daily Summary Data at https://www.epa.gov/outdoor-air-quality-data/download-daily-data. Daily Mean PM 2.5 Concentration (PM25) and Daily AQI (AQI) were gathered for the selected days at over 100 geolocated stations across California and were then assigned to rotating outage blocks using the nearest neighbor to the centroid of each blocks.

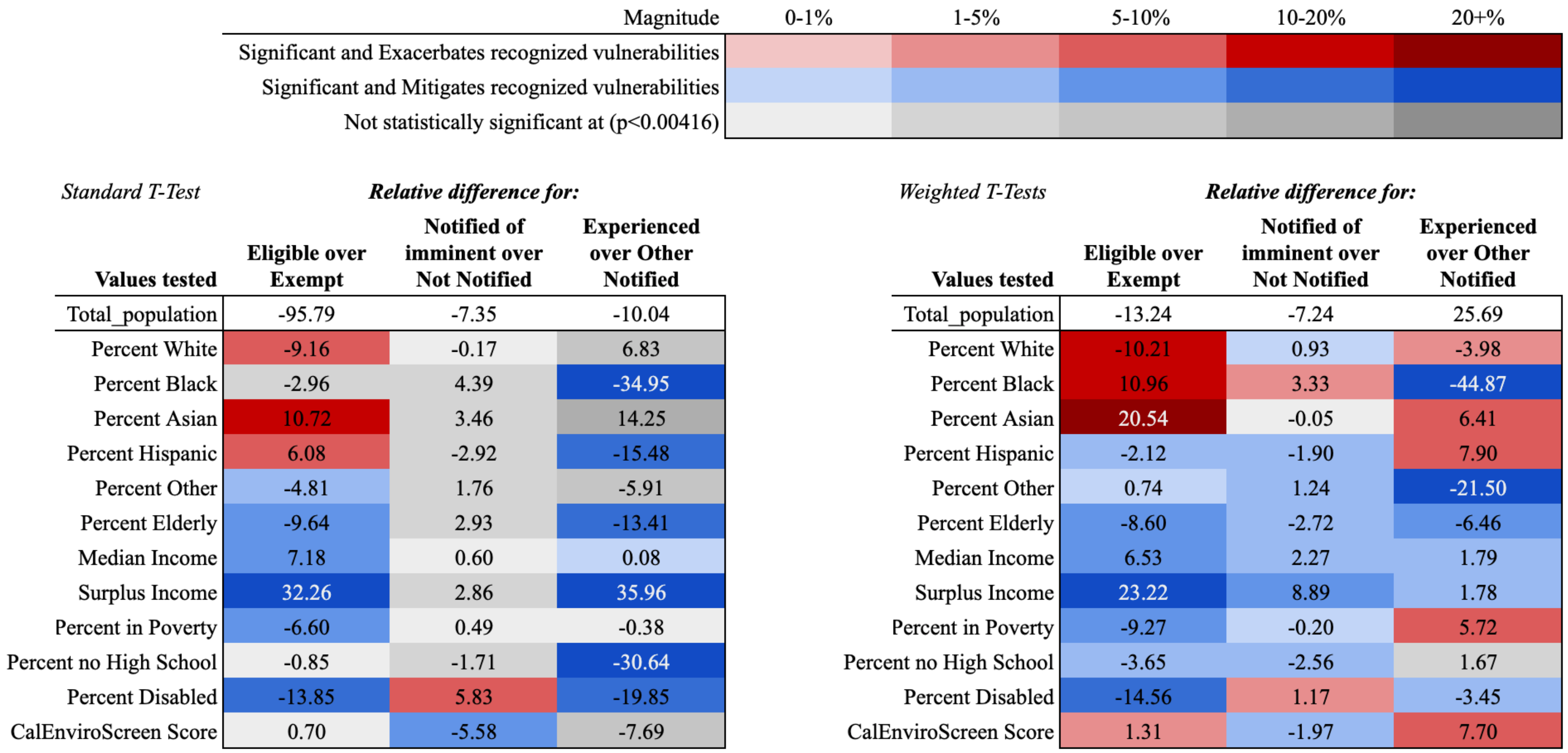
Legislation

Cal. Pub. Resource Code § 25700 - https://docs.google.com/document/d/1s6lrywehWnwkMwEzjZqcmHepE-CrH5Vlij3Iq1K3lF0/edit#heading=h.ecevuv8sxer5

C.3 Additional Figures

T-tests

The numbers in Figure C.1 indicate the percent difference in mean (left - unweighted, right - weighted) values of the higher risk category over the lower risk category. Color indicates statistical significance and whether the direction of relative difference exacerbates or mitigates recognized vulnerabilities. Shade indicates the magnitude of difference. An example interpretation for the value, color and shade of [Standard T-Test, Eligible over Exempt, Percent Asian] in Figure S2 would be: The unweighted mean percent of the population self-identifying as Asian was 10.72 percent larger (1.1072 times) for rotating outage blocks that were Eligible for outages (the higher risk category) than for rotating outage blocks that were Exempt from receiving outages (the lower risk category). The direction of this relative difference exacerbates recognized vulnerabilities, at a magnitude between 10-20%, and with a p-value less than 0.0041666.



Magnitude	0-1%	1-5%	5-10%	10-20%	20+%
Significant and Exacerbates recognized vulnerabilities	🟥	🟥	🟥	🟥	🟥
Significant and Mitigates recognized vulnerabilities	🟦	🟦	🟦	🟦	🟦
Not statistically significant at (p<0.00416)	▨	▨	▨	▨	▨

Standard T-Test

Values tested	***Relative difference for:*** Eligible over Exempt	Notified of imminent over Not Notified	Experienced over Other Notified
Total_population	-95.79	-7.35	-10.04
Percent White	-9.16	-0.17	6.83
Percent Black	-2.96	4.39	-34.95
Percent Asian	10.72	3.46	14.25
Percent Hispanic	6.08	-2.92	-15.48
Percent Other	-4.81	1.76	-5.91
Percent Elderly	-9.64	2.93	-13.41
Median Income	7.18	0.60	0.08
Surplus Income	32.26	2.86	35.96
Percent in Poverty	-6.60	0.49	-0.38
Percent no High School	-0.85	-1.71	-30.64
Percent Disabled	-13.85	5.83	-19.85
CalEnviroScreen Score	0.70	-5.58	-7.69

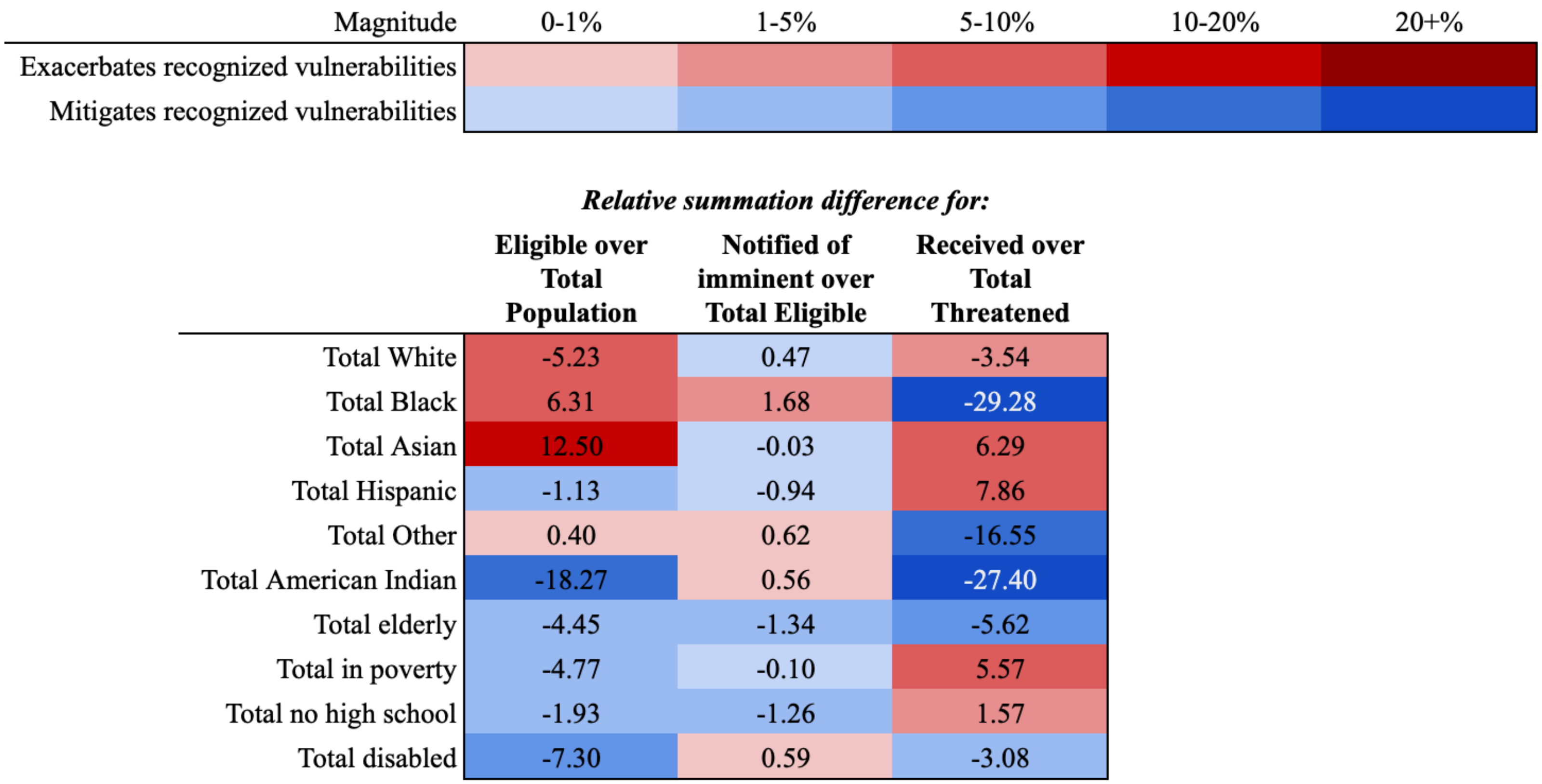
Weighted T-Tests

Values tested	***Relative difference for:*** Eligible over Exempt	Notified of imminent over Not Notified	Experienced over Other Notified
Total_population	-13.24	-7.24	25.69
Percent White	-10.21	0.93	-3.98
Percent Black	10.96	3.33	-44.87
Percent Asian	20.54	-0.05	6.41
Percent Hispanic	-2.12	-1.90	7.90
Percent Other	0.74	1.24	-21.50
Percent Elderly	-8.60	-2.72	-6.46
Median Income	6.53	2.27	1.79
Surplus Income	23.22	8.89	1.78
Percent in Poverty	-9.27	-0.20	5.72
Percent no High School	-3.65	-2.56	1.67
Percent Disabled	-14.56	1.17	-3.45
CalEnviroScreen Score	1.31	-1.97	7.70

Figure C.1: Significance, Magnitude, and Exacerbation/Mitigation of recognized vulnerabilities of Demographic and Environmental Risk compared at different levels of rotating outage planning and implementation

Summations

In Figure C.2, for each demographic and environmental risk variable we sum the total number of individuals in all rotating outage blocks across each of three binary categories. We then take the magnitude of difference in comparison to the total population. For example, the value at the intersection of Total Asian and Eligible over Total Population means that if one was Asian in PG&E's service territory, you were 12.5% more likely than the average population to receive the outages.



Magnitude	0-1%	1-5%	5-10%	10-20%	20+%
Exacerbates recognized vulnerabilities	🟥	🟥	🟥	🟥	🟥
Mitigates recognized vulnerabilities	🟦	🟦	🟦	🟦	🟦

Relative summation difference for:

	Eligible over Total Population	**Notified of imminent over Total Eligible**	**Received over Total Threatened**
Total White	-5.23	0.47	-3.54
Total Black	6.31	1.68	-29.28
Total Asian	12.50	-0.03	6.29
Total Hispanic	-1.13	-0.94	7.86
Total Other	0.40	0.62	-16.55
Total American Indian	-18.27	0.56	-27.40
Total elderly	-4.45	-1.34	-5.62
Total in poverty	-4.77	-0.10	5.57
Total no high school	-1.93	-1.26	1.57
Total disabled	-7.30	0.59	-3.08

Figure C.2: Summation results of demographic and environmental risk variables separated across analysis levels and whether the value exacerbates or mitigates recognized vulnerabilities

Temperature and Air Quality

Left: Maximum daily temperature in Farenheit was 10-20 degrees hotter than normal across the study area with the majority in 'Extreme Caution' or 'Dangerous' Conditions.

Right: While median air quality was moderate, there was a significant number of locations that had unhealthy Daily AQI.

Color-coded temperature ranges based on the National Weather Service's Heat Index that details the "Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity" for various temperatures assuming a 40% relative humidity. Color-coded air quality ranges based on the categories defined by the U.S. Air Quality Index on AirNow.gov

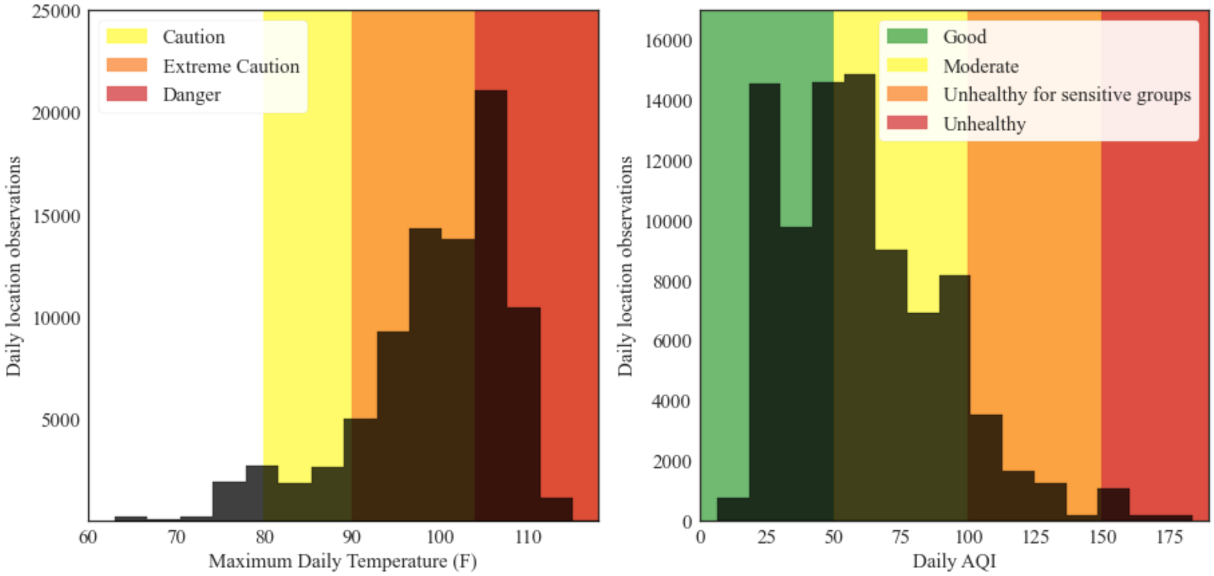


Figure C.3: Temperature and AQI across rotating outage blocks on threatened days

Temperature and Majority Ethnicity

Left: Across all locations and days, we found a consistent trend of eligible blocks having higher max daily temperatures than protected (exempt) blocks with the same majority ethnicity.

Right: We found that the Max Daily Temperature was lower for threatened White-majority blocks than not threatened, however the Max Daily Temperature was much higher for threatened Black-majority blocks than for not threatened ones.

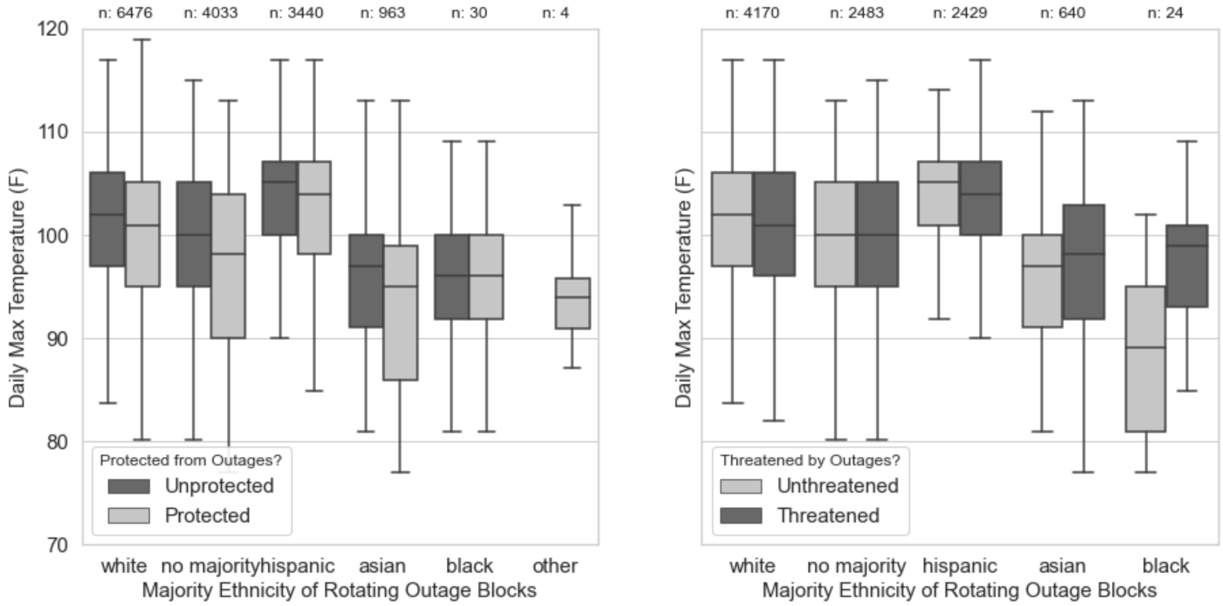


Figure C.4: Maximum Temperatures across Majority Ethnicities comparing Protected (Exempt) and Threatened (Notified) rotating outage blocks