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The Energy Equity Gap: Unveiling Hidden Energy Poverty

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Abstract

Income-based energy poverty metrics miss people's behavior (i.e., reducing energy consumption to limit financial stress). We introduce a novel method for calculating energy-limiting behavior in low-income households using a residential electricity consumption dataset. We first determine the outdoor temperature at which households start using cooling systems, the inflection temperature. Our energy poverty metric, the *energy equity gap*, is defined as the difference in the inflection temperatures between low and high-income groups. In our study region, we estimate the energy equity gap to be between 4.7°F and 7.5°F. In 2015-2016, within our sample of 4,577 households, we found 86 energy-poor and 214 energy-insecure households. In contrast, the income-based energy burden metric identified 141 households as energy insecure when the threshold was set to 10%. Only three households overlapped between the energy equity gap and energy burden measures. Thus, the energy equity gap reveals a hidden but complementary aspect of energy poverty.

Introduction

Energy poverty manifests in a high percentage of income spent covering energy bills, increased risk of electricity shutoffs, and a household's inability to maintain comfortable indoor temperatures or use desired services (e.g., air conditioning, heat, computers)^{1,2}. An often-overlooked space in energy poverty analysis lies in the cavity between metrics that measure financial stress (energy expenditure over total income, energy burden) and complete lack of energy services (utility shutoffs). Within this cavity are the households which limited their energy consumption to reduce financial strain. These households may appear to spend small amounts of their income on their energy bills while limiting enough energy to avoid having the utility cut their power supply. It is estimated that, annually, 1,300 people die every year in the U.S. from extreme heat³. In 2009 and 2010 alone, over 8,250 emergency room visits in the US were caused by heat stroke⁴, with low-income, minority, and elderly populations being disproportionately affected³. A large portion of these deaths could have been prevented if people could cool their homes properly^{5,6}. As the effects of climate change manifest themselves in heatwaves⁷ and deep freezes, communities will need to adapt (i.e., reduce their risk of illness and death⁸) by creating comfortable indoor temperatures within their homes. However, this depends on whether they can rely on their resources for adopting energy-efficient heating and cooling systems, meaning many vulnerable households who limit their energy consumption, potentially putting themselves at risk of heatstroke or hypothermia, may not qualify for energy poverty alleviation under current programs.

For example, in the US, the two main energy assistance programs, the Low Income Home Energy Assistance Program (LIHEAP) and the Weatherization Assistance Program (WAP), use an income threshold to determine eligibility^{9,10}. LIHEAP uses reduction in a household's energy burden, defined as the percent of income spent on energy expenditures, service loss prevention, and service restoration, to calculate the effectiveness of its assistance⁹. The WAP is geared more towards homeowners with its performance based on the number of households weatherized and post-weatherization surveys for those receiving assistance, with questions including change in energy burden and change in forgoing other necessities like food to pay energy bills^{9,11}. This suggests that these programs make an implicit assumption that people meet or try to meet their energy needs first compared to other necessities like food or healthcare. Neither of these programs takes into explicit account those who forgo energy to pay for other necessities, nor do they offer a clear definition of energy poverty⁹. The lack of consideration for households who forgo energy for other needs poses a limitation in identifying the multidimensional nature of poverty^{12,13} and reduces the options for policy intervention. In LIHEAP and WAP, spending

patterns are viewed as adequate ways to measure the effectiveness of these energy assistance programs^{9,11}. Here, we introduce a behavior-based energy poverty measure, which captures one critical aspect of energy poverty (i.e., energy-limiting behavior), providing a complementary metric to capture inequity within a region.

Existing energy poverty metrics

In a broad sense, energy poverty is defined as insufficient energy access due to lack of supply, low affordability, limited quantity, poor quality, unreliability, or a combination of these shortcomings. Existing energy poverty metrics fall into the following categories: A) primary or secondary, and B) relative or absolute, as seen in Figure 1. Here we define each category combination and provide some examples of each. A primary metric can be defined as a metric that directly utilizes consumer-level information. A secondary metric would require derivation to reach a conclusion. Secondary metrics include metrics that aggregate utility information or use weighted scoring for poverty indices. A relative metric compares the energy poverty status of two or more entities (i.e., country-to-country or household-to-household) or one with oneself (i.e., progress over time for one country). Finally, an absolute metric will provide a strict threshold for energy poverty.

Figure 1. Categories of energy poverty metrics

Relative-secondary metrics for energy poverty are often used to describe progress in energy poverty reduction in developing countries. One example is an access-consumption matrix at a national level¹⁴. Access-consumption matrices portray shifts in a country's energy profile, mainly the change in fuel utilization and how many people use each fuel. If more people are gaining access to energy services in an underdeveloped country, and more people are shifting from dirtier to cleaner fuels in developing regions, energy poverty is decreasing^{14,15}. This metric does not assume access to modern energy services. In contrast, it is best used for countries that are still building modern energy services and beginning their clean energy transition.

Relative-primary metrics can be scores from a survey asking questions on self-perception of energy poverty. For example, a survey done in Greece used indicators such as "inability to keep home adequately warm," "leakages, damp walls, mold," and "restriction of other essential needs" to solicit the subjective feeling of energy poverty^{16,17}. Compared with the 10% energy burden threshold, the study found that when a household is objectively categorized as energy-poor, they were more likely to respond "yes" for the subjective indicators. Another study explores the relationship between social relations and energy access, where a positive feedback loop exists between good social relations and higher quality energy access^{2,18}. However, drawbacks of survey-based metrics are long completion times and difficulty comparing the level of energy poverty experienced between households.

Absolute-secondary metrics often combine income-based metrics with sociodemographic factors and housing conditions to calculate a weighted score to measure energy poverty^{2,18}. However, because these measures (income-based, survey, and combined) single out those currently experiencing energy poverty, they can miss distributional changes over time and the severity of the energy poverty experience relative to the rest of the population. In addition, a limitation of these metrics is that they often focus on equality (i.e., all households reaching a certain status) but miss equity because they cannot identify how the energy-poor is doing relative to the non-energy-poor.

Absolute-primary metrics are often used to measure household-level energy burden, defined as energy expenditure over income. The underlying theory is that the more significant percentage of income spent on energy, the more energy-poor one is, similar to Engel's Coefficient for food expenditure¹⁹. The advantage of such a metric is that it indicates the economic burden of meeting energy needs and does not have a high computational burden. However, some limitations of using the energy expenditure metric include high sensitivity to energy prices and an inability to capture consumer behavior changes (i.e., price elasticity of demand)¹⁸. Additionally, income-based measures do not

distinguish between gross (i.e., pre-tax) and disposable income (i.e., post-tax and other mandatory charges like mortgage and rent). As a result, households may have the same pre-tax income level but have vastly different mortgage or rental costs, meaning that the 10% threshold on gross income will not transcend temporally nor spatially²⁰.

Despite the recent development of new metrics to capture consumer behaviors (e.g., under-consumption of energy and choice of thermal comfort), energy poverty analysis in developed countries has been dominated by absolute-primary economic-based metrics^{18,21,22}. Most energy poverty metrics in developed countries are income-based, with the most common being whether households spend 10% or more of their income meeting their energy needs or variations of this original energy poverty metric first proposed in 1991^{18,23}. Variations of the energy burden metric include the Low Income High Cost model, where a low-income threshold is added to the 10% threshold to determine a household's energy poverty status¹⁸. While these income-based metrics are widely used, they have a few shortcomings. First, they are sensitive to energy prices and mask the degree to which households change their energy consumption behavior following a price shift¹⁸. Second, and perhaps more importantly, the energy burden metric does not capture vulnerable low-income households who forgo energy usage to reduce financial stress. Lastly, income-based metrics miss essential dimensions of energy poverty, such as the inability to use enough energy to cool or heat homes to safe and desirable temperatures.

Most papers investigating the inability to satisfy a household's energy demand focus on electricity supply and reliability constraints in developing countries^{24–26} and energy affordability in developed countries^{1,27,28}. Within developed countries (i.e., those with close to 100% electricity supply access)²⁹, energy poverty and insecurity can manifest themselves in 1) electricity shutoffs resulting from nonpayment, 2) forgoing heating services due to financial strain and participating in unsafe practices (e.g., using stove or space heaters to heat space), 3) spending a large percentage of income on energy bills, and 4) difficulty adopting clean energy and efficient technologies^{17,30–32}. While multiple papers address the indicators of energy poverty^{9,33,34} and insecurity^{17,32}, we find a void of metrics that can identify energy-limiting households (i.e., those without comfortable indoor temperatures) who may put themselves at risk of heat-related illness, excess indoor moisture, mold growth, and other adverse health effects^{32,35,36} (e.g., respiratory illness and asthma).

Quantifying residential electricity consumption patterns

To capture those households left behind by income-based energy poverty measures, we propose a new energy poverty metric: the energy equity gap and illustrate its effectiveness for identifying households at risk for heat-related illness. Our study region in the US, Arizona, has long, high-heat summers and mild winters. Arizona has a higher level of heat-related illnesses (2944 heat-related ER visits in 2019³⁷ compared to cold-related illnesses (495 cold-related ER visits in 2019³⁸), leading us to focus our energy poverty analysis on the electricity sector due to this providing the bulk of cooling energy in the summer (air conditioning (AC) or fan usage). Identifying cooling system use is vital for addressing and planning for energy justice, which hinges on the proper distribution of benefits for a clean energy transition^{39–41} and an ability to mitigate the effect of heatwaves. We also introduce a tiered system for identifying and addressing the energy poverty needs of the most vulnerable households and contrast this with the existing income-based metric.

To the best of our knowledge, the energy equity gap is the first measure that investigates how consumer electricity consumption behavior across income groups shifts with temperature (i.e., consumers' temperature response functions). Previous research has investigated how consumers' temperature response functions (modeling energy usage against temperature or other climate factors) change with climate^{42,43}, but have not incorporated these functions into energy poverty identification. The energy equity gap metric takes into account the effect of weather on energy expenditure by examining trends in socioeconomic and ethnic groups. Since the energy equity gap measures electricity usage patterns between income groups within a region, it eliminates the effect of weather or temperature on electricity usage, which would occur when the study area is too large. Because the energy equity gap is a relative energy poverty metric, policymakers can have more targeted energy justice efforts by first identifying the outdoor temperature that places their region at risk for heat-related illnesses. Once the threshold has been set, policymakers can then use our relative metric to identify energy insecure households that are dangerously close to sinking into energy poverty and create proactive measures for reducing their burden. In addition to capturing household-level electricity consumption behavior, the energy equity gap allows for a cross-temporal comparison of population-level energy equity within a region.

The basis of the energy equity gap is household-level inflection temperatures. To best incorporate behavior into the new metric, we define the inflection temperature as the outdoor temperature at which a household starts using its cooling system as it shifts from spring to summer

temperatures, assuming there is no difference in comfort preference or need across income groups. To find the inflection temperature of each household, daily electricity consumption is modeled using average daily temperature, electricity pricing plan, holiday effects, and day-of-the-week and month-of-the-year fixed effects (see Methods). The minimum of the quadratic equation between electricity consumption and temperature after controlling for the covariates mentioned above is defined as the temperature at which people start using their cooling systems, the inflection temperature (Figure 2). This assumption stems from 1) heating and AC systems being the largest energy consumer within a household⁴², and 2) our study region having a warm and dry climate, with short, mild winters and long, high-heat summers. If the study region is in a colder climate or a climate with more distinct seasons, we recommend separating the year into two climate zones (i.e., spring-summer-fall and fall-winter-spring). To adapt the energy equity gap to identify heating system energy use, we would need to include information from the gas and oil sector. We leave the heating sector analysis for future work. We hypothesize that low-income households are more likely to endure higher temperatures before they start cooling their homes in the summer to save money and will thus have higher inflection temperatures.

Figure 2. Inflection temperature (star point) for daily electricity consumption and local daily mean outdoor temperature for one household in year 1 of our study (N=365). We note that our true temperature response function includes electricity price, weekend, holiday, day of the week, and month of the year effects. The inflection temperature is the minimum of the quadratic temperature response function between the residuals after controlling for these factors and outdoor temperature.

Redefining energy poverty and energy insecurity

The energy equity gap is defined as the difference between the highest and lowest median household inflection temperatures among all income groups (Figure 3) of the study region, a large metropolitan area in Arizona. We chose to use the median instead of the mean to desensitize the measure from outliers. The energy equity gap indicates the disparity in energy use across the income spectrum for a region while eliminating the effect of climate and electricity pricing. Within our metropolitan region, we assume the climate is uniform for households in the sample data, and everyone has access to the same energy services. Therefore, a sign of reduced energy inequity would be a narrowing energy equity gap, indicating that households are converging to a similar inflection temperature, thus reduced energy inequity.

The distribution of household-level inflection temperatures across income groups is shown in Figure 3. We see that the energy equity gap ranges from 4.7 – 7.5°F, highlighting that low-income groups are more likely to forgo cooling services until later in the summer than high-income groups. Furthermore, there is a statistically significant difference between the median inflection temperatures between each income group for all years, meaning there is little chance that the inflection temperature differences occurred by chance, verified using the Kruskal-Wallis test (see Methods).

Figure 3. The distribution of inflection temperature across income groups. The energy equity gap for each year is calculated as the difference between the highest and lowest median inflection temperature (indicated by the middle bar and number) among all income groups. The upper and lower lines on the boxes represent the 75th and 25th percentile of households. In all four panels, income group 1 had the highest, and income group 8 had the lowest median inflection temperature. The energy equity gap (EEG) is shown at the top of each panel. (a) 2015 – 2016 N = 4,577 households, (b) 2016 – 2017 N = 4,522 households, (c) 2017 – 2018 N = 3,852 households, (d) 2018 – 2019 N = 2,650 households.

Figure 4 illustrates the change in the energy equity gap across income groups for the four years in our analysis. The higher inflection temperatures further show low-income households tend to wait longer to turn on their AC units, pointing to underlying constraints, budget or otherwise, restricting their access to cooling. When cooling is restricted, it has been shown that buildings are at a higher risk for increased rates of mold, allergens, and fungi growth^{44,45} and that populations are at a higher risk for heat

stroke⁴⁶. As the energy equity gap shrinks and widens, we see the driving factor is that low-income households are getting worse off while high-income households are improving.

Figure 4. Energy equity gap (EEG) and median infection temperature changes across study years. Each data point represents the median infection temperature of the income group for that year.

In our analysis, we find that the energy equity gap narrowed by 1.2°F (-20.3%) between the first two years of our study, but then widened by 0.5°F (10.6%) and 2.3°F (44.2%) in the last three years of our study, as seen in Table 1. This may be caused by the delayed price elasticity of demand effects in year-to-year residential electricity price changes and a warming climate. As shown in Table 1, between years one and two, there was a 2.4 % increase in residential electricity prices and a 3.6% increase in cooling degree days. This corresponds to a 10.6% increase in the energy equity gap in year 3, caused mainly by low-income groups waiting longer to turn on their AC systems. Between years two and three, the residential electricity price rose again by 2.7% and cooling degree days by 2.5%, which corresponds to a 44.2% increase in the year's energy equity gap following the price increase. Both a higher temperature and higher electricity price will cause energy equity to deteriorate. Within our study population, low-income households are more likely to live in older residences (see Supplemental Information), which can contribute to more significant energy needs and financial strain required to cool the home.

Table 1. Temperature, electricity price, and energy equity gap shifts in Arizona. Max Average Monthly Max Temperature is the average maximum temperature of the hottest month in a year.

Arizona Metric	Change from year to year		
	Year 1 to 2	Year 2 to 3	Year 3 to 4
Max Average Monthly Max Temperature	1.0%	-0.2%	-0.2%
Cooling Degree Days (CDD)	3.6%	2.5%	-5.2%
Average residential electricity retail price (cents/kWh)	2.4%	2.7%	-2.7%
Energy Equity Gap	-20.3%	10.6%	44.2%

Price shifts will impact electricity consumption shifts within minority groups and those at the intersection of multiple vulnerable groups (e.g., low-income minority groups or low-income elderly populations) differently. Figures 5a and 5c show the median inflection temperature for each ethnicity and age group; Figures 5b and 5d show the energy equity gap within each ethnicity and age group, respectively. Comparing 5a and 5b, we see that the overall inflection temperature is low in the Black and Asian population, yet there is a wide energy equity gap for both, indicating high income disparity within the groups. In the Black population, we see increasing disparity followed by the 2.4% price increase from year 1 to 2, resulting in a 39% increase in the energy equity gap from year 2 to 3, earlier than the large price shock that affected the whole population. This indicates that the Black population is disproportionately affected by price shifts compared to the other ethnicities. The white population most closely resembles the overall population trend because white populations account for the majority (>70%) of residents in our sample. In general, we find that even when a minority group's median inflection temperature is low, there can be a high disparity between low and high-income populations (see Supplemental Information Figures S5-S7), evident in the Black and Asian population, where the former showed a decrease in overall median inflection temperature but a consistently high energy equity gap. The latter showed a uniform median inflection temperature but a rapidly increasing energy equity gap.

In Figures 5c and 5d, we investigate energy poverty and equity across age groups. There are statistically significant differences between median inflection temperatures across age groups ($p < E-23$),

as confirmed using the Kruskal-Wallis test (see Methods), indicating little chance that these variations occur solely due to chance. For the 18-24 age group, both the median inflection temperature ($>7^{\circ}\text{F}$) and the energy equity gap increased sharply ($>14^{\circ}\text{F}$) between 2018 and 2019, while for the older populations, the energy equity gap had little change in comparison. From an energy poverty targeting standpoint, this highlights that within the elderly population, all residents should be targeted to reduce inflection temperatures, while for the youngest age groups, the most effective poverty eradication policy would be to target low-income groups. For all age groups except for 75+, the later increase in the energy equity gap is from low-income households getting worse off and high-income households performing better, most evident in groups 18-24 and 25-34. The difference in inflection temperatures between age groups may be attributed to each age group's different temperature comfort levels. Elders may prefer warmer indoor temperatures, and cooling air from an AC system may inflame arthritis⁴⁷, but caution should be used when differentiating between a comfortably warm temperature and one that puts the resident at risk for a heat-related illness⁴⁸. Because there is a significant relationship between household income and inflection temperature, the high energy equity gap in younger age groups may be attributed to larger income inequality among young people.

Figure 5. Inter- and intra-group comparison of the inflection temperature and energy equity gap for ethnicity and age groups. Median inflection temperatures by [a] ethnicity and [c] age group show disparities across demographics. The energy equity gap highlights energy consumption behavior differences between high and low-income populations within their respective [b] ethnicity and [d] age groups. See Supplemental Information for more details.

We acknowledge that there is a chance that the inflection temperature and energy equity gap can be affected by indoor thermostat preferences. To account for varying preferences across ethnic and age groups, we investigate the inflection temperature disparities for different income groups within demographic distinctions (see Supplemental Information Figures S8-S13). For example, if one ethnic group preferred to turn on their AC units at a certain temperature, we expect to find a narrow vertical

distribution for the inflection temperatures (i.e., the Hispanic population in Supplemental Information Figure S6). On the other hand, if the different inflection temperatures represent inequity, we expect to find a wide vertical distribution (i.e., the Black and Asian population in Supplemental Information Figures S4-S5). Thus, the energy equity gap can highlight inequities across groups in a region. We present a more detailed discussion of preference limitation in the Supplemental Information notes.

We introduce a tiered system (Figure 6) to identify the households with the highest risk of heat-related illness and death. First, we assume the median inflection temperature of the highest income group is the ideal inflection temperature for this region. This assumption stems from the belief that the highest income groups are the least likely to constrain their budget and thus would initiate cooling systems earliest in the year. Then, similar to using a standard deviation, we define people with inflection temperatures between one and two energy equity gaps above the ideal inflection temperature to be in the low-risk zone. Next, households with inflection temperatures between two energy equity gaps and 78°F to be energy insecure. Within government buildings, it is recommended that 78°F degrees be the indoor set point⁴⁹, meaning this temperature setting may limit the risk for mold and allergen build-up, as well as heat-related illness and death. Finally, households with inflection temperatures higher than 78°F are defined as energy poor. We use the indoor 78°F comfort set point as our energy poverty threshold because households would need some degree of cooling above this outdoor temperature. We acknowledge that heat-mortality risk occurs at temperatures above 90°F⁵⁰, but our goal is to identify houses at risk for both health-related illness and death.

Using this tiered system, policymakers and utility companies can create more targeted weatherization aid programs. When we apply the tiers system to 2015-2016 data (Table 2), we identify 86 energy poor (1.9% of our sample) and 214 energy insecure households (4.7% of our sample).

Figure 6. Tier systems for energy poverty and insecurity identification using the energy equity gap

Comparing the energy equity gap to income-based measures

While US government assistance programs lack a clear definition for energy poverty, change in energy burden is often used to measure the outcome of these programs^{9,11}. When using the 10% energy burden threshold to identify energy-insecure households in our study region, we found that less than 3% of households were defined as energy insecure (Figure 7), of which over 70% reside in the lowest income group (<\$15,000) for all years in our study. Comparing the energy equity gap categorization with the energy burden measure of individual households, we find that few households (≤ 20) were identified as energy insecure or energy poor under both metrics (Table 2). The energy burden metric categorizes more households as energy insecure, but our tiered system identifies more energy-poor households who may be placing themselves at risk by limiting cooling-associated energy use. The energy burden metric misses more than 95% of those with high inflection temperatures and, therefore, a higher risk of extreme heat exposure. Of that 95%, around half of the households are in one of the three low-income groups (<\$35,000). There are energy insecure households identified in the non-low-income groups, which hints that while some households are not classified as low-income, they may have low disposable income (e.g., high mortgage or rent costs) and limit their financial burden by reducing their energy consumption. This further highlights the need for multiple energy poverty and insecurity measures to determine financial and behavioral energy consumption trends in energy-insecure households.

We also compared eligibility for LIHEAP and WAP and households in the 2nd tier of the energy equity gap metric. In our dataset of 6,002 households, 871 qualified for LIHEAP and 1,553 qualified for WAP using their respective income threshold⁹. We found that 48-72 households each year have high inflection temperatures but are not eligible for LIHEAP. Because WAP has a higher income threshold than LIHEAP, all households that qualify for LIHEAP also qualify for WAP, so this range reduces to 29-53 households when comparing the energy equity gap and WAP. Many of these missed households are just on the edge of the low-income threshold but have dangerously high inflection temperatures, making them vulnerable without assistance.

Figure 7. Energy poverty measured using the energy burden (EB) metric. The x-axis measures the percent of income a household spends on electricity. The red dotted line indicates the 10% income spending threshold. Most households spend between 1% and 10% of their income on electricity.

Table 2. Comparing the energy equity gap (EEG) and financial-bases energy assistance categories

(Number of households in each category)		2015- 2016	2016- 2017	2017- 2018	2018- 2019
	Total households	4,577	4,522	3,852	2,650
	Energy equity gap (EEG) low risk zone	2,719	2,143	1,889	1,619
	EEG 1 st tier: Energy insecure	214	631	484	42
	EEG 2 nd tier: Energy poor	86	83	57	59
	Households with energy burden $\geq$ 10%	141	135	111	88
	EEG low-risk zone households with energy burden $\geq$ 10%	94	59	64	55
	EEG 1 st tier households with energy burden $\geq$ 10%	6	16	9	1
	EEG 2 nd tier households with energy burden $\geq$ 10%	3	4	1	2
Missed Households	EEG 1 st and 2 nd tier households with energy burden < 10%	274	587	286	93
	EEG 2nd tier households not eligible for LIHEAP	72	63	48	48
	EEG 2nd tier households not eligible for WAP	53	37	33	29

Limitations of Analysis

Energy poverty exists in multiple forms, leading to numerous limitations in any quantification method. Here we present a discussion of the limitations of our methods and opportunities for future improvements. Uncertainties in using the iteration of the energy equity gap outlined in this paper include the lack of heating data from the natural gas provider. From the dataset provided by the electric utility, we gather that 60% of households in this study use electricity for both cooling and heating, while the remaining most likely use natural gas or oil for heating. However, we did not find the type of heating system to be a significant indicator of household inflection temperatures. Thus, the model used to calculate the inflection temperature still stands for this particular electricity-based dataset (see Methods), particularly for a high-heat area like Arizona where heat-related illness and death is significantly higher than cold-related ones^{37,38}.

Housing characteristics that relate to the energy efficiency of the home⁵¹ (e.g., number of windows, insulation, wall thickness, finishing material, the orientation of the home, etc.) were not included in the dataset but would be valuable additions to future utilities data collection effort. We did find a relationship between residence age and income group, where a large proportion of low-income households lived in older homes (see Supplemental Information Figure S3), which could contribute to higher inflection temperatures and less overall household energy efficiency. A limitation of our study is the inability to quantify the actual indoor temperature of homes. We hypothesize that the energy equity gap could be wider than our analyses suggest due to the urban heat islanding effect^{52,53}, with low-income households being more exposed to high heat due to less shading and vegetation in their urban environments.

Conclusion

The energy burden metric targets households who limit other necessities to meet energy needs but misses out on those who limit energy spending to meet other needs. The energy equity gap fills this void by identifying who chooses to endure higher temperatures in the summer and how their behavior changes due to price spikes and weather changes. The two types of metrics should be used in conjunction to identify households experiencing multiple types of energy poverty, those who forgo other needs to meet their energy demand, and those who forgo energy to meet other necessities. By considering behavior patterns in addition to spending patterns, we are able to keep at-risk populations from falling through the cracks of policies intended to help them. As nations continue designing policies

to achieve SDG 7, regions need a straightforward method to evaluate the current level of energy poverty from an economic, consumption, and behavioral perspective.

By grouping households by income and energy equity gap severity, policymakers and utility companies can target the most at-risk households requiring urgent financial help with energy bills and weatherization. The value of the energy equity gap is that it creates the possibility of a sliding-scale energy poverty assistance program (see Supplemental Information), which could set weatherization targets for the population based on their ability to adapt to extreme weather events (e.g., heatwaves) and how they are performing relative to others in the region. For example, if primary policies were designed to target households with an inflection temperature above 78°F and spend more than 10% of their income on meeting their energy needs, this could reduce financial strain and heat-related illnesses in the region. Secondary policy targets should focus on households with low income and above-average inflection temperatures. These households are likely to suffer from multiple forms of energy poverty and insecurity but are not at high risk for heat-related death.

On the other hand, high-income households with high inflection temperatures may be best suited for discounted weatherization programs due to their likelihood of having limited disposable income. When adapting the energy equity gap to other regions, electricity consumption may be sufficient for similarly high-heat regions. However, we will need to consider gas, electric, and potentially other fuels used for heating to estimate total energy consumption for colder climates. Calculating the energy equity gap requires the same information for the traditional energy poverty metric, so the cost to compute and utilize the energy equity gap would be marginal.

In the ever-evolving discussion around equity, justice, and policy, we need to study and develop policy that answers the needs of those historically and systemically marginalized. We can start by identifying those falling through the policy cracks by casting a finer net. The energy equity gap contributes to the discussion of existing energy poverty metrics by capturing a region's relative progress while including the households that income-based metrics may have left behind. By targeting the population with higher-than-ideal inflection temperatures with smart policies, regions will more effectively eradicate energy poverty and assist their residents in adapting to climate change.

Methods

Data

The data was provided by Salt River Project, a large utility company in Arizona. The dataset comprises two parts: first, hourly electricity consumption in kWh from May 2015 to April 2019 for 6000 households and the billing plan for each household; second, a comprehensive Residential Equipment and Technology Survey conducted in 2017 for those households. The survey included information on household sociodemographic information, dwelling characteristics, and appliance ownership.

Salt River Project provides different billing packages from which customers can choose based on their preferences. Each billing package has its own pricing rules and condition. The billing packages can be categorized into Basic Rate Plan, Time-of-Use Plans, and Prepaid Plans. Pricing rules were integrated into the consumption dataset to account for energy consumption patterns based on electricity pricing, where a uniform weighted average electricity price is calculated across 24 hours of the day.

The hourly electricity consumption was aggregated into daily consumption. Daily consumption information was then coupled with daily average temperatures for the study region, compiled from WeatherForYou.com⁵⁴.

Inflection Temperature

The inflection temperature is defined as the outdoor temperature where a household shifts from using its heating system to its cooling system. We recognize that there may be a temperature range where the household uses neither heating nor cooling, and the base level energy consumption during that period would be temperature-independent⁴³. In this context, the inflection temperature is still an indicator of the shift in energy consumption behavior. A household's inflection temperature is calculated using a nonlinear regression model (equation 1), which estimates daily electricity consumption of household i on day t ($E_{i,t}$) based on the following variables: daily average temperature (T_t), electricity price based on the billing plan of the household and season ($P_{i,s}$), dummy variables of whether day t is a holiday (H_t), day-of-the-week fixed effects (δ_t), and month-of-the-year fixed effects (μ_t). When modeling day-of-the-week and month-of-the-year dummy variables, Wednesday and March were dropped, respectively, to prevent collinearity.

$$E_{i,t} = \alpha + \beta_1 \times T_t + \beta_2 \times T_t^2 + \beta_3 \times P_{i,s} + H_t + \delta_t + \mu_t \quad (1)$$

The quadratic equation models the relationship between daily electricity consumption and daily average temperature. We chose a quadratic relationship because it best coincides with the shape of the electricity consumption and temperature data when plotted (Figure 2). The convex shape of the curve confirms the notion that when electricity consumption is highly correlated with temperature (see supplemental information). The inflection temperature is the minimum electricity consumption point (equation 2) and signifies the outdoor temperature a household must experience before initiating their AC units.

$$T_{inf} = T_t \text{ when } f'(E_{i,t}) = 0 \quad (2)$$

The outliers of the inflection temperature model are defined as any household with an inflection temperature below 30°F or above 120°F, because these are the outdoor temperature limits measured in the study region. An inflection temperature outside of this bound may indicate incomplete electricity consumption data. Within our study, we filtered out 0.5% in year one, 1.6% in year two, 1.2% in year three, and 0.2% in year four from our analysis due to their classification as outliers. There are a total of 6,002 households across the four years of study, but not all households have complete data for all years, which is why the total number of households in Table 2 decreased. One reason for the incomplete data may be that households started or stopped service midway with this utility company.

Computing the Energy Equity Gap

The energy equity gap quantifies the relative energy consumption behavior differences between low and high-income groups using the inflection temperatures. We hypothesized that lower-income households are more likely to have higher inflection temperatures due to financial limitations and a desire to delay cooling their homes to reduce their energy burden (i.e., percent of income spent on energy services). After calculating the inflection temperature (T_{inf}) for each household for one year, we group households by income. The energy equity gap for year y , G_y , is the maximum median inflection temperature ($\max(T_{inf,median})$) minus the minimum inflection temperature ($\min(T_{inf,median})$) among all income groups.

$$G_y = \max(T_{inf,median}) - \min(T_{inf,median}) \quad (3)$$

We hypothesized that lower-income households are more likely to have higher inflection temperatures. To test our hypothesis, we performed a Kruskal-Wallis test, or a one-way analysis of

variance on ranks, for significance. A significant result from a Kruskal-Wallis test demonstrates that one sample stochastically dominates another, and the differences between sample medians are statistically different. Tests were also performed on median inflection temperatures of ethnicity and age groups, with P-values shown in Table 3. When we group the households by income, we see significant P-value results for all four years, which indicates that the difference in median inflection temperatures of income groups have a close to 0% chance of solely being random (i.e., they are statistically significant). We see similar results when we group the sample population by age, which means age may also be a strong indicator of inflection temperature. Therefore, we cannot rule out that age may play a role in electricity consumption habits (e.g., older people may prefer to turn on their AC at a higher temperature), which would affect the inflection temperatures seen across groups. That being said, when computed within an age or ethnicity group, the energy equity gap can highlight when members are experiencing worsening poverty (i.e., the gap is widening), or when members of the group are adapting to temperature changes in a similar fashion (i.e., the gap is narrowing). While the ethnicity p-values are not on the same order of magnitude as income or age groups, we find that there is less than a 1% chance that the variation between ethnic groups is solely due to chance for years one, two, and four, and less than 6% for year three, thus indicating high statistical significance.

Table 3. P-values from the Kruskal-Wallis test on median inflection temperatures of income, ethnicity, and age groups.

Grouping	2015-2016	2016-2017	2017-2018	2018-2019
<i>Income</i>	4.8E-32 ****	3.6E-30 ****	5.6E-24 ****	2.0E-18 ****
<i>Ethnicity</i>	9.0E-03 **	2.2E-05 ****	6.0E-02	2.3E-02 *
<i>Age</i>	3.4E-46 ****	5.5E-54 ****	5.0E-35 ****	1.8E-24 ****

Computing the Traditional Energy Poverty Metric

We define the traditional energy poverty metric as the percent of income spent on satisfying electricity demand. We calculate the proportion of energy expenditure of each household for each year using income, residential electricity price, and energy consumption. For each household, the utility company provides the income bracket each household falls into. We use the midpoint of each income

group to estimate the percent of income spent on energy consumption. For the lowest income group (< \$15,000), \$10,000 was taken as the midpoint; for the highest income group (> \$150,000), \$175,000 was taken as the midpoint.

$$S_{i,y} = \frac{\sum E_{i,t} \times P_i}{I_{i,m}} \quad (4)$$

$S_{i,y}$ is the energy expenditure over income of household i in year y , $E_{i,t}$ is the daily electricity consumption of household i on day t . P_i is the average electricity price of the billing plan of household i . $I_{i,m}$ is the midpoint estimate of income for household i .

Data Availability

Records of mean daily outdoor temperatures were retrieved from WeatherForYou.com by way of web scraping. The electricity consumption and survey data are from the Salt River Project. As they are restricted by a non-disclosure agreement, they are available from the authors upon reasonable request and with permission from the SRP.

Code Availability

All data and models are processed in Python 3.8.5. The figures are produced in R studio (based on R 4.0.3). All custom code is available on GitHub at <https://github.com/Pa223/The-Energy-Equity-Gap>.

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Author Contributions

Dr. Nock conceived the research idea and designed and oversaw the research process. Cong designed and performed the analysis. Cong wrote and revised the initial draft of the paper. Dr. Nock and Dr. Qiu reviewed and revised the paper. Dr. Xing collected and cleaned the data.

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Ethics declaration

The authors declare no competing interests.

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