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An incandescent truth: Disparities in energy-efficient lighting availability and prices in an urban U.S. county

Tony G. Reames*, Michael A. Reiner, M. Ben Stacey

University of Michigan, School for Environment and Sustainability, 440 Church Street, Ann Arbor, MI 48109, USA.

HIGHLIGHTS

- Bulb availability and price were explored across poverty strata and store types.
- 130 in-store surveys were conducted in Wayne County, Michigan.
- Energy-efficient bulbs were less available in high-poverty areas and smaller stores.
- Energy-efficient bulbs were more expensive in high-poverty areas and smaller stores.
- Cost to upgrade from incandescent to LED was 2 times higher in high-poverty areas.

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ABSTRACT

In the U.S. lighting represents about 9% of the average household's primary energy consumption and 20% of the average household's energy bill. Lighting in U.S. homes is in a state of transition with steady growth in the adoption of more energy-efficient lighting technology, such as, compact florescent lamps (CFL) and light-emitting diodes (LEDs). However, the adoption of energy-efficient lighting is not equitably distributed across socioeconomic groups, with poorer households less likely to adopt than higher-income households. This case study in Wayne County, Michigan explores the lack of parity in energy-efficient lighting adoption from an energy justice perspective by evaluating distributional disparities in light bulb availability and price in 130 stores across four poverty strata and five store types for a more holistic understanding of potential barriers for poorer households. We found that (1) energy-efficient bulbs were less available in high-poverty areas and smaller stores; (2) energy-efficient bulbs were more expensive in high-poverty areas and smaller stores; (3) upgrade costs from incandescent and halogen lamps (IHLs) to CFLs or LEDs were higher in high poverty areas; and (4) both poverty and store type were significant predictors of LED availability, while store type was the most significant predictor of LED price variability. We suggest several ways that the development and implementation of energy efficiency policies and programs may consider these disparities that affect access and affordability, in order to achieve a more just energy-efficient transition.

1. Introduction

Individual participation in the transition to a low-carbon, cleaner energy future, requires household adoption of energy-efficient technologies. For prolific adoption trends to materialize, new technology must be recognized as being both cost effective and socially accepted [1,2]. It is therefore critical to understand energy transitions from a socio-technological perspective, exploring the interaction between humans and technology [3]. Moreover, if transitions are to be equitable, or just, the implementation of new energy technologies, policies, and programs, must consider the impact on and participation of poor and other disadvantaged populations [4].

Residential lighting is one technology undergoing a rapid transition centered on enhanced energy efficiency. Indoor lighting has experienced major technological shifts over time, from the 125-year-old incandescent to the highly-efficient lighting technology we know today [5–7]. In the U.S., lighting accounts for 10% of residential electricity consumption, 9% of the average household's primary energy consumption, and 20% of the average household's energy bill [8]. The U.S. Energy Information Administration (EIA) estimates that by 2040 the average household will use less than half the electricity for lighting as it did is 2016, as households upgrade from less energy-efficient

* Corresponding author.
E-mail address: treames@umich.edu (T.G. Reames).

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incandescent and halogen lamps (IHLs) to more energy-efficient compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs) [8]. Additionally, government policies have required advancements in lighting energy efficiency and incentivized decreased energy waste as critical means for achieving national security, economic, health and environmental goals. For instance, the federal Energy Independence and Security Act (EISA) of 2007 legislated requirements for increased lighting energy efficiency. Subsequently, manufacturing of lighting technology has evolved and adapted to meet these and other standards [5].

Lighting upgrades are often the first residential energy efficiency measure pursued, offering one of the easiest ways to cut household energy bills due to ease of replacement, relatively low upfront costs, and short paybacks periods. Thus, many energy efficiency programs substantially focus on lighting upgrades as a cost-effective, entry-level measure when compared to more capital-intensive efficiency measures [2,9,10]. In addition to an economic case for lighting upgrades, an environmental case also exists that supports widespread replacement of older, less efficient lighting [11]. According to some, the ultimate goal is to replace all IHLs, and even CFLs, with LEDs; despite increased efficiency of IHLs required by EISA, because LEDs last 25 times longer and consume 75% less electricity [5,12,13]. In one estimate, converting all conventional lighting to LEDs could reduce energy consumption by 1000 TW h yr^{-1}, the equivalent of about 230 500-MW coal plants and reduce greenhouse gas emissions by roughly 200 million tonnes [14].

Although policy and market forces are driving growth in LED adoption, only 29% of U.S. households use at least one LED bulb in their home [15]. Moreover, industry reports indicate patterns of energy-efficient lighting adoption are not equitable across socioeconomic groups. Lower income households (those earning less than $50,000 per year) are less likely than higher income households to purchase LEDs [16]. Instead, growth in market demand for LED lighting is being driven by young and higher income consumers [16].

The lack of parity in energy efficient lighting technology across socioeconomic groups has real implications for the imbalance in residential energy dynamics that exist between these groups. First, although low-income households consume 16% less energy, annually, when compared to non-low-income households, low-income households have an energy use intensity (EUI), or the amount of energy consumed per square area, that is 27% greater than non-low-income households [17]. Since EUI is a proxy for energy efficiency, it is clear that while low-income households consume less energy, they are consuming that energy less efficiently. Secondly, this variance in residential energy efficiency comes with a social price, which can have both direct and indirect impacts on energy affordability [18]. The average low-income household has an annual energy burden, or the percentage of household income spent on energy bills, ten times that of non-low-income households, 10.4% compared to a 1.2% [17]. Energy burdens exceeding 6% are considered unaffordable [19]. The relationship between energy consumption, efficiency, and burdens cannot be understood by a simple economic explanation. Disparities in energy consumption, efficiency and burdens have clear spatial distributions in urban areas that are closely related to the demographic and socioeconomic characteristics of place, and to pervasive racial and income segregation that are commonplace in many U.S. urban areas [20–22].

Therefore, it is crucial to employ an energy justice perspective that aims to establish a more holistic understanding of the factors that perpetuate energy efficiency disparities across socioeconomic groups by exploring the hidden justice implications for rapidly transitioning technologies. Thus, this study explores the retail dynamics and distributional inequities of residential lighting technology availability and price across socioeconomic groups and store types.

1.1. Background

Socioeconomic disparities in access to energy efficient technology is a fundamental aspect of energy *in*justice. Thus, it is important to frame the relationship between energy efficient technology access and price with socioeconomic disparities in energy efficiency and energy burdens from an energy justice perspective, particularly the issue of distributional injustices. Walker and Day [18] introduce three interacting distributional issues that lead to inequalities in access to adequate levels of energy services: (1) inequalities in income; (2) inequalities in energy prices; and (3) inequalities in technology energy efficiency. Additionally, Sovacool and Dworkin [23], posit that the “simplest and most accepted” principles of their energy justice framework are availability and affordability (p. 367).

Exploring the availability and price of energy-efficient lighting, as a widely understood and basic form of residential energy consumption, may reveal broader barriers facing poorer consumers in the adoption of technology that could reduce their energy consumption and improve energy affordability. Studies have identified a number of barriers that seek to explain socioeconomic disparities in the adoption of energy-efficient technologies and subsequent disparities in energy efficiency and burdens, particularly those barriers that impede poor households from participating in beneficial programs [1,6,7,21,24–28]. Barriers may fall into a number of categories, including, market, institutional, social/cultural, behavioral, and political/regulatory [1,6,7,21,24–27]. Two of the most cited barriers to energy-efficient technology adoption are higher initial costs and information deficits [1,6,7,24,25,27,29]. Although the adoption of more efficient lighting is recognized as “low-hanging fruit,” for many households, particularly the poor, the upfront cost to upgrade from an incandescent to a more energy-efficient bulb is a significant barrier [30,11]. Additionally, a lack of sufficient information, or information deficit, can impede adoption of technology and even participation in beneficial programs [1,9,21,26]. This is especially true in urban, poor neighborhoods which often lack access to technical information and knowledge about new technology [30,31]. Such barriers have been cited as reasons why CFL bulbs never successfully penetrated residential households as the accepted better lighting technology, despite their greater efficiency over incandescents; however, LEDs have had a better fate and have surpassed CFLs as the preferred energy-efficient lighting upgrade [1,5,16].

In the 1980s, consumers treated lighting as a commodity and often purchased replacement bulbs at grocery stores instead of large retail chains like Wal-Mart and Home Depot, yet grocery stores were less likely to stock energy-efficient bulbs, like CFLs, which was a barrier to early adoption [5]. However, today, little is known about the distribution of light bulb retail dynamics and the potential barriers that may prevent parity in energy-efficient lighting adoption across socioeconomic groups and store types. The type of store in which merchandise is sold can be an important predictor of its availability and price [32,33]. Furthermore, retail patterns and store types vary by neighborhood income; high-poverty neighborhoods lack large retail stores and chains which often sell products as lower prices, and are instead associated with smaller retail stores which often sell products at higher prices [37]. Additionally, a well-established body of literature on disparities in availability and price of healthy food across socioeconomic groups and story types, often referred to as food justice studies, provides a model for understanding availability and price disparities in energy-efficient lighting. Food justice studies find that retail patterns, including spatial distribution, store type, and access to personal vehicles, result in either limited availability of and access to healthier food options or paying higher prices for healthier foods at stores located in high-poverty neighborhoods [33–38].

1.2. Study objectives

Despite much interest in residential lighting upgrades, there has been little systematic empirical research documenting variations in the availability and price of light bulbs across socioeconomic groups and store types. To the authors’ knowledge this is the first local-level study based on in-store data collection. This gap in the literature on the transition to more energy-efficient lighting justifies the necessity for an energy justice framed study.

Thus, with this paper we aim to contribute to discussions concerning social equity in energy transitions by addressing two relevant questions: are energy-efficient light bulbs differentially available, and do energy-efficient light bulb prices vary to the disadvantage of those living in socioeconomically deprive neighborhoods? We focus on variations by poverty and store type as potential predictors of availability and price for three standard residential light bulb types. We explore these questions within the urban context of Wayne County, Michigan. Our results confirm that within an urban area disparities exist in availability to and price of more energy-efficient lighting across socioeconomic groups and store types. Understanding barriers to energy-efficient technology adoption parity resulting from retail a dynamics perspective is beneficial for both policy and program design.

The remainder of the paper is structured as follows: Section 2 describes the study area, data and statistical methodology. Section 3 presents study results. Section 4 discusses key results. Section 5 concludes with policy implications and areas of future research.

2. Material and methods

To study relationships between light bulb availability, price, and household incomes, we conducted in-store surveys of retailers in an urban U.S. county, clustered at the U.S. Census Zip Code Tabulation Area (ZCTA) and stratified by percentage of households living below the federal poverty level (FPL)[1] to distinguish areas in which a greater number of lower income households reside (high-poverty strata) from those areas in which a greater number of higher income households reside (low-poverty strata).

2.1. Description of study area

This study was undertaken in Wayne County, Michigan. With 1.8 million residents (approximately 703,000 households), Wayne County is the most populous county in Michigan with nearly 20% of the state's population, and is the 19th-most populous county in the U.S. [39,40]. Like many urban U.S. counties, Wayne County is a large and socially heterogeneous area, comprising of a major central city, Detroit, surrounded by the affluent communities and suburbs, such as, the Grosse Pointe communities, and sizeable suburban cities of Dearborn, Livonia and Canton. Also, common to urban counties, socioeconomic characteristics sharply contrast between Detroit and its suburbs. The poverty gradient across the county is shown in Fig. 1. While 22.4% of Wayne County households are below the FPL, 36.4% of Detroit households are below the FPL. Furthermore, Pew Research on Social and Demographic Trends found that the Detroit metropolitan area is the sixth most income-segregated metro in the U.S. [41].

Concerning disparities in energy affordability in Wayne County, nearly 40% of lower income households fall behind on their utility payment, compared to roughly 14% of higher income households, and lower income households are seven times more likely to experience a utility shutoff than higher income households [42]. Wayne County households living below the FPL have energy burdens typically between 16 and 30%, compared to households above the FPL with energy burdens of 8.8% or less [19]. Additionally, spatial and socioeconomic disparities in residential energy efficiency exist in Wayne County. On average, homes in higher poverty areas exhibited higher EUIs than home in lower poverty areas of the county [20].

Recent state policies, like the Michigan Clean and Renewable Energy and Energy Waste Reduction Act (2016), which amended a similar 2008 Act, required energy utilities to establish energy waste reduction (EWR) programs, often achieved through energy efficiency measures or programs that target customer behavior, equipment, devices, or materials. A major component of utility-managed EWR programs has been the promotion of upgrading less-efficient IHLs with CFLs and LEDs as a cost-effective measure for achieving energy efficiency goals. In fact, according one utility, over half of its residential electricity savings were earned through CFL and LED lighting upgrades. Many other states have similar energy policies. The American Council for an Energy Efficient Economy (ACEEE) found that in the largest 51 cities in the U.S., 49 have utility-administered low-income energy efficiency programs and 40 of them offered low-income lighting upgrades [10].

2.2. Sample

We conducted 130 in-store surveys in 19 ZCTAs between January 15 and February 15 of 2017. The store sample was drawn in four steps. First, 703 retailers in Wayne County considered most likely to sell residential light bulbs were identified using the business and consumer data provider *ReferenceUSA* by selecting the following retail trade Standard Industrial Classification (SIC) codes (which indicate a company's primary type of business): 5000 (Durable Goods); 5200 (Building Materials, Hardware, Garden Supply); 5311 (Department Stores); 5331 (Variety Stores); 5399 (Misc. General Merchandise Stores); 5411 (Grocery Stores); and 5912 (Drug Stores).[2] Second the 68 populated ZCTAs in the county were assigned to 4 strata according to the percentage of households in the ZCTA living below the FPL: stratum 1, < 10%; stratum 2, 10–20%; stratum 3, 20–40%; and stratum 4, ≥ 40%. Third, the 703 identified stores were clustered by ZCTA. Fourth, for each poverty stratum, ZCTAs were randomly selected until the total number of stores reached a minimum threshold of 20% of the total number of identified stores for that stratum. For example, in poverty stratum 1 (*< 10% of households below the FPL)* 5 ZCTAs were randomly selected before the sum of stores in those selected ZCTAs reached the 20% minimum threshold of identified stores for the stratum. This strategy resulted in a sample of 189 stores in 19 ZCTAs. Table 1 illustrates the sample selection of stores and ZCTAs by poverty stratum. During data collection, 58 stores included in the sampling frame were either no longer open for business or did not sell light bulbs. Since all stores in the sampling frame where identified from the same source and by the same method, we assumed that the same percentage of identified stores in each stratum may either be closed or did not sell light bulbs and thus our final number of surveyed stores would satisfy our goal of surveying a minimum of 20% of identified stores in each poverty stratum. For example, 39% of stores in the poverty stratum 1 sampling frame were closed or did not sell light bulbs, thus we assumed that 61 (or 39%) of the 158 identified stores in poverty stratum 1 were closed or did not sell light bulbs, resulting in 97 identified stores and 23% of stores surveyed in the stratum.

For simplification, we categorized stores across 5 types: large retail stores; hardware stores; variety stores; pharmacies; and small retail stores. Descriptions of each store type and the number of stores surveyed in each category are found in Table 2. Variety stores represented the largest proportion of stores in the county, followed by pharmacies. Additionally, the distribution of store types across poverty strata is detailed in Table 2. The majority of large retail stores and pharmacies

[1] According to the U.S. Census Bureau (2016), the federal poverty threshold for a family of four is $24,563 a year.

[2] Data collection procedures and instruments were pilot-tested in 10 retail locations to test variability in light bulb availability and price by retail location and classification. The pilot study verified variability in light bulb availability and price by retail location and classification. In addition, we determined that convenience stores accompanying fueling stations, were unlikely to carry residential light bulbs and/or serve as a primary retail location for light bulb purchases. Consequently, while these stores are classified by SIC 5411, those with Primary SIC description, Convenience Stores, were excluded from the sampling frame.

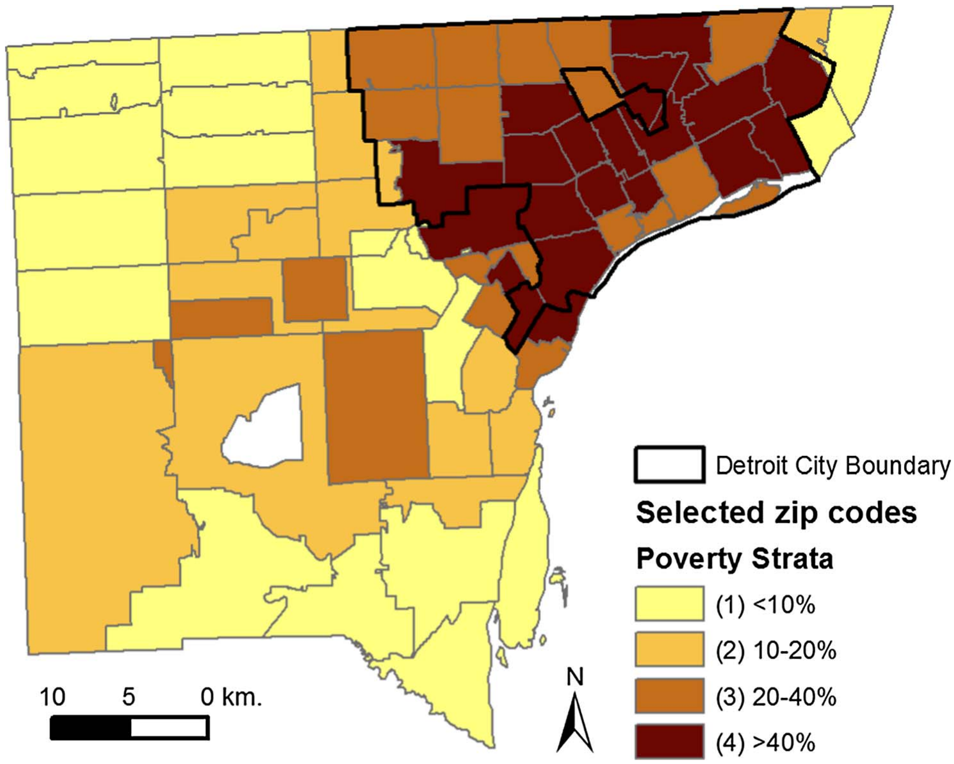

Fig. 1. Distribution of percent of households living below the FPL, by zip code in Wayne County, Michigan.

Table 1
Sample selection of stores and ZCTAs by poverty strata.

Poverty Strata	Total No. ZCTAs	Total No. Identified Stores	Sample of Identified Stores	Sampled ZCTAs	No. Identified Stores (Revised)	Final No. Surveyed stores
1	19	158	36 (23%)	5	97	22 (23%)
2	13	146	43 (30%)	2	119	35 (30%)
3	16	181	54 (30%)	6	122	36 (30%)
4	20	218	56 (26%)	5	144	37 (26%)
Total	68	703	189 (27%)	18	482	130 (27%)

Note: Poverty strata represents% of households below FPL, *1* = < 10%; *2* = 10–20%; *3* = 20–40%; *4* = ≥40%.

thus they may be more dependent on stores within close proximity [37].

2.3. Data collection

Availability and price data were collected for incandescent and halogen lamps (IHLs), compact fluorescent lamps (CFLs), and light-emitting diodes (LEDs). Only bulbs with a brightness level, or lumen range, of 600–900, representing the equivalent replacement of a 60-watt standard indoor light bulb, were included in this study.

Trained, two-person data collection teams conducted in-store surveys in assigned ZCTAs. To reduce data collector bias we employed three primary quality assurance and quality control measures. First, a standardized data collection instrument was developed for in-store observations. The instrument included multiple lines to record the following data: (1) light bulb type (IHL, CFL, or LED); (2) lumens; (3) total package price; (4) number of bulbs in the package; and (5) sales price, if applicable. Data was collected directly from product packaging

Table 2
Description and count of store types, and distribution of store types and lack of personal vehicle access by poverty strata.

Store Type	Description	No. of Stores Surveyed by Type	Distribution of store type by Poverty Strata			
			1	2	3	4
Large Retail Store	Includes all physically large general merchandise, home improvement, and large grocery stores; usually part of a local, regional or national chain	23 (18%)	9	9	4	1
Hardware Store	Includes smaller stores that sell general lines of tools and builders' hardware	14 (11%)	1	3	5	5
Variety Store	Includes stores that sell a variety of merchandise in the low and popular price ranges; typically, not departmentalize; do not carry a complete line of merchandise	47 (36%)	3	13	13	18
Pharmacy	Includes stores that primarily sell pharmaceuticals, but also carry general merchandise	34 (26%)	9	9	10	6
Small Retail Store	Small shops which do not fit into the above categories	12 (9%)	0	1	4	7
Households that lack personal vehicle access, by poverty strata			4.5%	7.5%	17.6%	26.5%

Note: Poverty strata represents% of households below FPL, *1* = < 10%; *2* = 10–20%; *3* = 20–40%; *4* = ≥40%.

were located in low-poverty strata 1 and 2. The majority of hardware, variety, and small retail stores were located in high poverty strata 3 and 4. Additionally, households in high-poverty strata have less access to personal vehicles compared to low-poverty strata (as shown in Table 2, and the retail shelf for all packages meeting the 600–900 lm range criteria. In each surveyed store, all packages meeting these criteria were recorded, for example, when package options varied in number of bulbs (e.g., 2-pack CFL and 8-pack CFL) all packages were recorded. Second, the goal of surveying in pairs was to provide consistency and accountability in data collection procedures and improve accuracy. Third, the authors and data collection teams met after each survey day to debrief, collect and review the data collection instrument.

2.4. Statistical analysis

Availability comparisons were conducted as percentages of stores that had a light bulb type available across poverty strata and store type. Price comparisons were for the average unit price (irrespective of brand and inclusive of sales price at the time of survey) for all packages of each light bulb type across each poverty strata and store type. A series of bivariate statistical tests were used to explore disparities in light bulb availability and price based on poverty strata and store type. Z-tests were used for pairwise comparisons to analyze differences in light bulb type availability proportions between poverty strata and store types. One-way ANOVAs were used to test differences in mean bulb price between poverty strata and store types. Lastly, since the predictors poverty strata and store type may be correlated, it is important to consider their simultaneous effects on availability and price using multivariate analysis techniques. Logistic regression was used to model how poverty strata and store type affect the probability of LED availability and linear regression was used to model how poverty strata and store type affect LED price.

The statistical software package Stata 14.2 was used for data management and analysis. Since sampling was not proportional to the number of stores within the county, rather a proportion of stores by stratum, sampling weights were constructed as the inverse of the sampling fraction representing the number of sampled zip codes (z_1, z_2, …, z_n) per stratum out of the total number of zip codes per stratum in the county (Z_1, Z_2, …, Z_n). The unit of analysis is the poverty strata or store type, and each data point represents a bulb package (e.g., a single bulb package, a 2-bulb package, a 4-bulb package).

3. Results

3.1. Light bulb availability

Bulb availability by type and poverty strata is summarized in Table 3. Across the county, IHLs were available in 93% of stores, CFLs in 60% of stores, and LEDs in 75% of stores. The majority of stores (≥89%) in every stratum carried IHLs. CFLs were available in a majority of stores in poverty strata 2, 3 and 4 (≥61%), but available in only 45% of stores poverty stratum 1. There were no statistically significant differences for either IHL or CFL availability between poverty strata. Availability of LEDs, however, did vary significantly by poverty strata and was lower in high-poverty strata (3 and 4) when compared to low-poverty strata (1 and 2), ranging from 57% to 91%. LEDs were 34% (z = 2.75, $p < 0.01$) more available in poverty stratum 1 than poverty stratum 4. LEDs were also 22% (z = 2.33, $p < .05$) and 34%(z = 3.33, $p < 0.01$) more available in poverty stratum 2 than in poverty strata 3 and 4, respectively.

Within strata, energy-efficient bulbs, CFLs and LEDs, were significantly less available in high-poverty strata than IHLs. In poverty stratum 3, there was a 28% (z = 2.42, $p < 0.05$) gap in CFL availability and 20% (z = 1.88, $p < 0.05$) gap in LED availability when compared to IHL availability. In poverty stratum 4, IHLs were available in 95% of stores, while CFLs and LEDs were 30% (z = 3.00, $p < 0.01$) and 38% (z = 3.49, $p < 0.001$) less available than IHLs, respectively.

Light bulb availability by store type is summarized in Table 4. The majority of stores (≥86%) carried IHLs with no significant differences in availability between store types. Across all store types, CFL availability was less than both IHL and LED availability, ranging from 8% in small retail stores to 77% in variety stores. The lower availability of CFLs confirms their decline in the marketplace, in fact, CFL availability was 35% lower for large retail stores than variety stores, which had the largest proportion of stores carrying CFLs (z = −2.07, $p < 0.05$). A majority of stores, by type, carried LEDs, except for small retail stores, of which none carried LEDs. LEDs were least available in hardware stores (71%), which was 23% (z = −1.99, $p < 0.05$) less than pharmacies, which had the highest proportion of stores carrying LEDs (94%).

Bulb type availability varied within store types. More energy-efficient bulbs, CFL and LED, were available in lower proportions than were IHLs. The most varied availability among bulb types was in large retail stores where IHLs were available in 57% more stores than CFLs (z = 3.98, $p < 0.001$) and 22% more stores than LEDs (z = 2.37, $p < 0.05$). In pharmacies, IHLs were available in 35% more stores than CFLs (z = 3.71, $p < 0.001$). The largest variance in availability of more energy-efficient bulbs was in small retail stores where a 91% gap existed between the proportion of stores carrying IHLs and those carrying CFLs (z = 2.24, $p < 0.05$).

3.2. Light bulb prices

The mean bulb price and standard deviation for each bulb type by poverty stratum is presented in Table 5 and by store type in Table 6. The bold font italicized numbers indicate the least expensive mean bulb price and the bold font underlined numbers indicate the most expensive mean bulb price. The mean bulb price across the county was $1.96 for IHLs, $4.32 for CFLs, and $6.23 for LEDs.

Poverty strata was statistically associated with bulb price variations for both IHLs and LEDs, but not for CFLs. The mean IHL price was $0.49 ($p < 0.05$) less expensive in high-poverty stratum 4 than in low-poverty stratum 2. The inverse is observed for mean price variation for LEDs across poverty strata. The mean LED price in high-poverty strata 3 and 4 was $2.49 ($p < 0.05$) and $2.67 ($p < 0.01$), respectively, more expensive than LEDs in poverty strata 1. Although the mean price for CFLs was more expensive in poverty stratum 4 than poverty stratum 1, there was not a statistically significant difference in mean price across poverty strata.

The mean cost across the county to upgrade from a less energy-efficient IHL to a more energy-efficient CFL or LED was $2.36 and $4.27, respectively. Comparable to mean bulb price variations across poverty strata, the cost to upgrade to a more energy-efficient bulb was more expensive in high-poverty strata than low-poverty strata. An IHL to CFL upgrade cost ranged from $1.58 in poverty stratum 1 to $3.12 in poverty stratum 4. Similarly, the upgrade cost from an IHL to a LED ranged from $3.10 in poverty stratum 1 to $6.24 in poverty stratum 4. The mean upgrade cost from an IHL to a CFL was $1.54 more expensive in poverty strata 4 when compared to mean upgrade costs in poverty strata 1. The mean cost to upgrade from an IHL to a LED was 2 times more expensive in poverty stratum 4 than in poverty strata 1 Table 5. In the Supplemental material, Fig. 1 illustrates the bulb price trend across poverty strata, by type, and how the decreasing price of IHLs and increasing price of LEDs creates a widening gap in upgrade price from

Table 3
Availability of light bulbs types, by poverty strata.

	All Poverty Strata	1		2		3		4	
	%	%	N	%	N	%	N	%	N
IHL	93	100	22	91	32	89	32	95	35
CFL	60	45	10	63	22	61	22	65	24
LED	75	91	20	91	32	69	25	57	21

Note: Poverty strata represents% of households below FPL, *1* = < 10%; *2* = 10–20%; *3* = 20–40%; *4* = ≥40%.

Table 4
Availability of light bulb types, by store type.

	All Store Types	Large Retail		Hardware		Variety		Pharmacy		Small Retail	
	%	%	N	%	N	%	N	%	N	%	N
IHL	93	100	23	86	12	87	41	100	34	92	11
CFL	60	43	10	64	9	77	36	65	22	8	1
LED	75	78	18	71	10	81	38	94	32	–	–

Table 5
Mean Light Bulb Price and Upgrade Cost, By Poverty Strata.

	All Poverty Strata	1	2	3	4	Significance (ANOVA)
IHL	1.96 (0.07)	2.10 (0.91)	**2.12 (1.55)**	1.70 (0.76)	***1.63 (0.72)***	–*
CFL	4.32 (0.23)	***3.68 (2.43)***	4.40 (3.08)	3.96 (1.81)	**4.75 (2.94)**	
LED	6.23 (0.27)	***5.20 (3.51)***	6.17 (4.77)	7.69 (4.71)	**7.87 (5.24)**	–**
Mean Upgrade Cost						
IHL to CFL	2.36	***1.58***	2.28	2.26	**3.12**	
IHL to LED	4.27	***3.10***	4.05	5.99	**6.24**	

Notes: Mean (SD); ***$$*** = least expensive; **$$** = most expensive.
Poverty strata represents% of households below FPL, *1* = < 10%; *2* = 10–20%; *3* = 20–40%; *4* = ≥40%.
The bold font italicized numbers indicate the least expensive mean bulb price and the bold font underlined numbers indicate the most expensive mean bulb price.
* $p < 0.05$.
** $p < 0.01$

low- to high-poverty strata.

Store type was significantly associated with the mean price of all light bulb types Table 6. Small retail stores were the least expensive stores to purchase IHLs. The mean price for IHLs at large retail and variety stores was less expensive than the mean IHL price across all store types. At small retail stores, IHLs were $1.01 less than large retail stores ($p < 0.01$), $1.64 less than hardware stores, $0.83 less than variety stores ($p < 0.05$), and $2.13 less than pharmacies ($p < 0.001$). Variety stores sold IHLs for $0.80 less than hardware stores ($p < 0.05$). IHLs were more expensive at pharmacies than large retail stores and variety stores, $1.12 and $1.30, respectively ($p < 0.001$).

Large retail stores had the least expensive CFLs and LEDs. The mean prices for CFLs at hardware and variety stores were also less expensive than the mean CFL price across all store types. CFLs were $2.10 ($p < 0.01$) and $1.46 ($p < 0.05$) more expensive at pharmacies than they were at large retail and variety stores, respectively. CFLs at small retail stores were $9.67 ($p < 0.01$), $8.88 ($p < 0.05$), and $9.03 ($p < 0.01$) more expensive than large retail, hardware, and variety stores, respectively. Variety stores were the only other store type with a mean LED price less expensive than the mean LED price across all store types. LEDs were $7.06, $3.89, and $5.86 more expensive at pharmacies than at large retail, hardware and variety stores, respectively ($p < 0.001$). The mean price for LEDs at hardware stores was $3.15 ($p < 0.001$) more expensive than large retail stores.

Pharmacies were the most expensive place to purchase IHLs and LEDs and the second most expensive place to purchase CFLs. Hardware stores were the only other store type with IHL and LED mean prices more expensive than their mean price across all store types. Only one small retail store carried CFLs costing $12.99, making it not only the most expensive CFL, but the most expensive mean price for all bulb types and store types surveyed.

3.3. LED availability and price

Since a primary objective of this paper is to further understand the disadvantage poorer households face in adopting energy efficient bulbs, Table 7 presents the results of two multivariate regression models examining the simultaneous effects of poverty strata and store type on LED availability and price. Model 1 shows the results of a logistic regression model for LED availability. Exploring data for all 853 light bulb packages, both poverty strata and store type influence LED availability. LED availability is reduced in all poverty strata (2, 3 and 4) when compared to poverty stratum 1 ($p < 0.5$). Likewise, LED availability is reduced, when compared to large retail stores, in variety stores and pharmacies ($p < 0.5$), but not hardware stores. Model 2 shows the results of a linear regression mode for LED price over all 317 LED bulb packages. Interestingly, poverty strata have no significant relationship with LED price when store type is in the same model. Instead store type is the main driver in LED price variations. When compared to large retail stores, hardware stores increase LED price by $3.02, variety stores increase LED prices by $1.09, and pharmacies increase LED prices by $7.04 ($p < 0.05$).

As mentioned earlier, the majority of large retail stores and pharmacies are located in low-poverty strata, and that households in high-poverty strata have less access to personal vehicles thus being more dependent on stores within close proximity, such as hardware and variety stores. Thus, we examine the effect of store type alone on LED availability and price, see model results in Supplemental Material Table 1. We found that the odds of LED availability were reduced for both variety stores (0.33, $p < 0.001$) and pharmacies (0.43, $p < 0.001$) when compared to large retail stores. We also found the mean LED bulb price was statistically more expensive at all other store types when compared to large retail stores. For instance, LED bulbs were $1.20, $3.17, and $7.06 ($p < 0.01$) more expensive at variety

Table 6
Mean light bulb price, by store type.

	All Store Types	Large Retail	Hardware	Variety	Pharmacy	Small Retail	Significance (ANOVA)
IHL	1.96 (0.07)	1.66 (0.52)	2.28 (1.63)	1.48 (0.40)	**2.78 (1.65)**	***0.65 (0.32)***	–***
CFL	4.32 (0.23)	***3.32 (2.37)***	4.11 (2.26)	3.96 (1.25)	5.42 (4.09)	**12.99 (0)**	–***
LED	6.23 (0.27)	***3.97 (2.54)***	7.13 (5.34)	5.17 (2.30)	**11.03 (4.95)**	–	–***

Notes: Mean (SD); ***$$*** = least expensive; **$$** = most expensive.
The bold font italicized numbers indicate the least expensive mean bulb price and the bold font underlined numbers indicate the most expensive mean bulb price.
*** $p < 0.001$.

Table 7
Regression models exploring influence of poverty strata and store type on LED availability and price.

Strata	Model 1: LED Availability			Model 2: LED Price		
	Odds Ratio	S.E.	*p*	*β*	S.E.	*p*
1	***Reference***			***Reference***		
2	0.69	0.13	0.047*	0.56	0.45	0.22
3	0.51	0.13	0.007*	−0.26	0.77	0.74
4	0.54	0.13	0.011*	0.85	0.72	0.24
Store Type						
Large Retail	***Reference***			***Reference***		
Hardware	0.99	0.27	0.976	3.02	0.98	0.002*
Variety	0.41	0.09	0.000*	1.09	0.47	0.021*
Pharmacy	0.49	0.1	0.000*	7.04	0.67	0.000*
Small Retail	***NA***					
Constant	1.35	0.21	0.051	3.65	0.28	0.000*
N	**853**			**317**		
Wald chi^2	**52.32**[a]		0.000*	***NA***		
F	***NA***			**23.26 (6, 310)**[b]		0.000*
R^2	**0.05**			**0.38**		

Note: Model 1, logistic regression, DV: LED = 1. Model 2, linear regression, DV = LED price. Poverty strata represents% of households below FPL, *1* = < 10%; *2* = 10–20; *3* = 20–40%; *4* = ≥40%.

* $p < 0.05$.

[a] The Wald chi-square test tests the null hypothesis that the constant equals 0. This hypothesis is rejected because the p-value is smaller than the critical p-value of .05.

[b] The F-test of overall significance indicates whether a linear regression model provides a better fit to the data than a model that contains no independent variables. The numbers in parentheses are the Model and Residual degrees of freedom.

stores, hardware stores, and pharmacies, respectively, when compared to large retail stores. Thus, households in high poverty strata may find LED bulbs less available, but when they do find them, they would spend more than if they had easier access to large retail stores located outside of their neighborhoods.

4. Discussion

In summary, we found that energy-efficient lighting availability and price varied across Wayne County, Michigan, with limited availability and higher prices disproportionally experienced in high-poverty areas. While it appeared with the passage of EISA that incandescent bulbs would become obsolete and the more efficient CFLs or LEDs would proliferate, a 2014 Congressional spending bill included language that blocked many of the energy efficiency standards of EISA from taking effect, thus, as we found, IHLs remain available and the least expensive lighting option in a majority of all store types and across poverty strata. It is important to note that the IHLs currently manufactured and sold are about 25% more energy-efficient than their predecessors. While, the availability of CFLs across store types and poverty strata was primarily consistent, the availability in low-poverty strata 1, and at both large and small retail stores was lower than the county average availability. Additionally, CFL were less available than IHLs and LEDs across all store types and all poverty strata, except high-poverty stratum 4. This lower availability of CFLs tracks reports that consumers are moving away from CFLs as a smaller number of consumers have heard of CFLs as an energy-efficient upgrade option when compared to LEDs [16]. Availability of LEDs varied significantly across poverty strata and within poverty strata, mainly affecting high-poverty areas. LEDs were less available as areas became poorer and within poor areas LEDs were less available than IHLs and even CFLs in the poorest areas. Across store types, LED availability was consistent; however, none of the small retail stores surveyed, located primarily in the poorest areas, carried LEDs, while 92% of them carried IHLs. The impact of both poverty and store type on LED availability was confirmed by the logistic regression model.

Light bulb price patterns point to potential barriers to the adoption of energy-efficient lighting in higher poverty neighborhoods. We found a negative correlation between IHL price and poverty. IHLs became less expensive as area became poorer, which could entice consumers in poorer neighborhoods to continue to purchase IHLs. In addition, the price to upgrade from an IHL to both CFLs and LEDs was positively correlated with poverty. Again, a clear trend and widening gap exists between low- and high-poverty strata in the price of IHLs and LEDs, and upgrade cost differentials, as illustrated in Supplemental Material Fig. 1. Thus, creating additional barriers to parity in energy-efficient bulb adoption. In the poorest area, there was a $6.24 mean price difference between an IHL and a LED. This is a huge upfront cost in areas where 40% or more of the households live in poverty and roughly 27% do not have access to a personal vehicle to increase the likelihood of traveling to stores outside their immediate vicinity. Unsurprisingly, large retail stores, located primarily in areas with less poverty, offered the least expensive CFLs and LEDs. These stores, typically national, regional, or local chains, generally offer larger discounts on items compared to specialty or smaller retails, because they can purchase wholesale bulk items and stock larger supplies of items at a lower price. The most expensive CFLs and LEDs were found at pharmacies and small retail stores, primarily located in poorer areas. Although bivariate analyses found significant relationships between both poverty strata and store type on light bulb price, when considering both simultaneously, store type was the stronger influence on variations in LED price, with hardware stores, variety stores, and pharmacies being significantly more expensive than large retail stores, again disproportionately affecting the poorer households who are more likely to shop at local stores. Regression models exploring the influence of store type illustrate how store types, other than large retail stores, reduced the odds of LED bulbs being carried, and of those store types carrying LED bulbs, bulbs were $1 to $7 more expensive on average than LED bulbs in large retail stores. The lack of large retail stores and personal vehicle access in high-poverty areas is similar to findings in food justice studies that identify these issues as a barrier to healthy food access and to paying higher prices for healthy foods.

Qualitative observations, captured by some survey teams, provide further insight into barriers faced by consumers in poor neighborhoods. There were noticeable differences between stores in low- versus high-poverty areas with regards to in-store displays and employee knowledge and engagement. In low-poverty area, several large retail store chains, particularly large home improvement stores, had illuminated displays showcasing easily interpretable information with graphics describing the qualities, features and benefits of each lighting technology option. Employees in these stores were equipped with a depth of knowledge about the advantages of CFLs and LEDs. In contrast, stores located in high-poverty areas lacked in-store lighting advertisements or clearly displayed information, and store clerks generally, not always the case, had less knowledge about differences in lighting technologies. This is an important distinction as industry surveys indicate that 64% of consumers rely on in-store displays, employee interactions, and product packaging as the primary source of information for lighting purchases [16], these observations of in-store access to information offer important implications about potential barriers to poor consumers making informed decision about energy-efficient lighting technology adoption and purchases.

5. Conclusions

This study explores disparities in availability and price of energy-efficient lighting technology within Wayne County, Michigan. Drawing from research methodologies applied within other academic spaces, this work provides a critical assessment of technology availability and affordability by store type and poverty level. As energy-efficiency upgrades are a vital tool that shapes our current energy transition, more research is needed to determine whether there exist certain economic and spatial barriers to household energy efficiency upgrades. This analysis can be extended to other technologies to determine whether access to affordable energy-efficient devices is equitable across all populations.

Our study found that:

- there were significant disparities in the availability and cost of LED bulbs between high- and low-poverty strata;
- the availability and cost of less-efficient IHL bulbs were most prevalent in high-poverty strata; and
- store type was a significant factor in predicting the cost and availability of LED bulbs, while larger retail stores provided the greatest availability and lowest costs.

These findings reinforce the notion that the cost of upgrading to more energy-efficient technology is more costly in higher poverty urban areas. We elaborate below on the policy implications of such findings and opportunities to further apply this analysis.

These results raise energy justice concerns with significant implications for state and federal policies that aim to create economic, social and environmental benefits from energy efficiency transitions, which often rely on the assumption that social costs and benefits produced by the proliferation of energy efficient technologies are distributed equitably. The ability to benefit from the transition to more energy-efficient lighting is not equitably distributed from the perspective of access or affordability. Thus, policies and programs that aim to increase residential energy efficiency should be deliberate in their consideration of energy justice implications, seeking proactive ways to explore and incorporate measures to prevent unintended social equity impacts into policy, regulation and program implementation.

This study is important for urban areas in states which require residential energy efficiency programs that heavily rely on efficient lighting measures for achieving state-legislated energy savings targets. As mentioned above, ACEEE found that 81% of utility-administered low-income energy efficiency programs offered some type of low-income lighting upgrades. Yet participation and knowledge challenges remain. The disparities identified in this study offer an opportunity to enhance the process by which energy savings are measured and evaluated for energy efficiency programs which differentiate the benefits provided to low- and high-income consumers from interventions such as LED light bulb subsidies in stores. Commencement or improvement of programs offering no- to low-cost LEDs to poor households or providing in-store rebates and discounts in stores in high-poverty areas may achieve additional energy and cost savings, not otherwise captured under the traditional assumptions of equal accessibility and affordability. In current state regulations, energy savings are differentiated between socioeconomic groups as the varying levels of free riders, or likelihood of adopting technology without additional incentive. However, evaluating free ridership is challenging and as this study finds there are differential upfront costs in upgrading lighting technology that present additional barriers to adoption for poor consumers. Accurately quantifying the energy savings achieved through programs that differentiate low- and high-income consumers is crucial to achieving equity in state energy efficiency goals. There is also an opportunity to improve technology education in poorer neighborhoods and the retail stores in the neighborhoods on the benefits of more energy-efficient lighting technology that could be funded at either the state- or utility-level to mirror the displays and employee knowledge found at large retail stores.

While our study may not necessarily be generalized to other counties, there are certain characteristics that define urban U.S. counties that may render similar results. A deeper analysis of the relationship between the spatial distribution of retail store types and the shopping preferences of poor households would provide additional understanding of the impact of the spatial distribution of store types on adoption of LEDs. Further insight would also be gained from studies of these patterns of availability and price in urban areas with both similar and different patterns of residential segregation [22]. For instance, we initially considered racial segregation as a factor in this study; however, percentage of nonwhite population was an insignificant variable throughout the analysis although some studies have found significant relationships between race and energy efficiency in two different urban counties with similar segregation patterns [20,21,26]. While we might assume that counties with lower levels of residential income segregation would have less variability in energy-efficient lighting availability, because poverty was a significant predictor of availability when controlling for store type, variability in LED prices across the county would be dependent of the distribution of store types, regardless of the poverty distribution.

As energy efficiency continues to gain momentum across the U.S. and globally as a highly cost-effective energy resource and is implemented as a long-term strategy in energy regulation, social equity concerns must have an integral role throughout the policy development and implement processes. This not only impacts light bulbs, but other energy efficient technology, like appliances, for which poorer households are more likely to have older, less-efficient appliances. Further research is necessary to understand the impact that availability and price have on decision-making in poor and other disadvantaged communities and what the implications are for state and federal policy. For instance, the findings of study pose a disconcerting question concerning unintended consequences of policy aimed at an efficient energy transition: did changes to the EISA requirement to improve incandescent efficiency, rather than ban them, perpetuate energy inequities for poor communities?

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.02.143.

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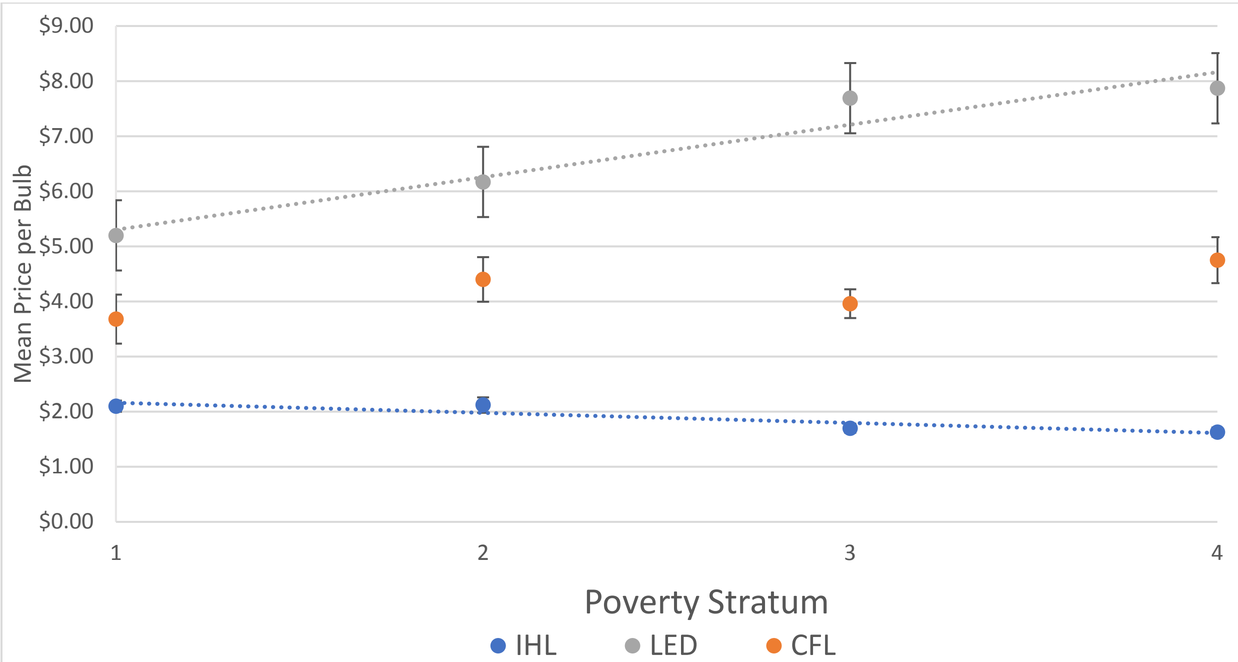
Supplementary material



Supp. Mat. Figure 1. Mean Light Bulb Price, By Poverty Strata illustrating trend lines. Error bars are quantified by standard error.

Supp. Mat. Table 1.
Regression models exploring influence of store type on LED availability and price.

	Model 1: LED Availability			**Model 2: LED Price**		
Store Type	**Odds Ratio**	**S.E.**	***p***	***ß***	**S.E.**	***p***
Large Retail	***Reference***			***Reference***		
Hardware	0.82	0.22	0.456	3.17	0.98	0.001*
Variety	0.33	0.07	0.000*	1.20	0.38	0.002*
Pharmacy	0.43	0.08	0.000*	7.06	0.62	0.000*
Small Retail	***NA***					
Constant	1.06	0.14	0.663	3.97	0.23	0.000*
N	**853**			**317**		
Wald chi^2	**38.04**		0.000*	***NA***		
F	***NA***			**45.02 (3, 313)**		0.000*
R^2	**0.04**			**0.38**		

Note: Model 1, logistic regression, DV: LED=1. Model 2, linear regression, DV= LED price.