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Distributional disparities in residential rooftop solar potential and penetration in four cities in the United States

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ABSTRACT

Single-family residential rooftop solar adoption in the United States has not occurred equitably across the country, nor across socioeconomic and demographic groups. In response, state and local governments have developed solar equity programs, primarily focused on increasing adoption by low- and moderate-income (LMI) households. This study merged national datasets that estimate rooftop solar potential, the distribution of rooftop solar systems, and census tract- level socioeconomic and demographic characteristics to answer three questions. First, how are spatial distributions of rooftop potential and penetration similar and different across cities? Second, how is rooftop penetration distributed across non-LMI and LMI communities in different cities? Third, how do the relationships between rooftop penetration and local socioeconomic and demographic characteristics, identified as barriers to solar adoption, differ? Using GIS, bivariate and multivariate analyses, these questions were examined in four US cities – Riverside and San Bernardino, California, Washington, DC, and Chicago, Illinois – to understand both universal and distinct local manifestations. Findings include: higher rooftop potential existed in some LMI communities; higher rooftop potential did not necessarily translate to higher rooftop penetration, especially if higher potential was in LMI communities; and beyond income, other socioeconomic and demographic characteristics such as race/ethnicity, limited English proficiency, age of housing stock, and internet access were associated with rooftop penetration. While there remains great potential for expanding rooftop solar to LMI households and communities, understandingexplor the local dynamics of solar potential and penetration may inform better policy development and implementation.

1. Introduction

During the last decade, residential solar photovoltaic (PV) adoption continued to grow in the United States. According the United States Energy Information Administration (EIA), small-scale (systems generating less than one megawatt) residential PV capacity increased significantly reaching 7.4 GW in 2016, a 43% increase over 2015 and was forecasted to reach 13.7 GW at the end of 2018 [1]. The Solar Energy Industries Association (SEIA) reported that the residential PV market grew 7% in 2018, and the EIA forecasts that 11 GW of capacity will be install during 2020 and 2021 [2,3]. In addition to the cost to install solar dropping more than 70% over the last decade, various state and federal policies support the forecasted industry growth, such as California's new 2020 mandate requiring that all new single-family home construction have rooftop solar.

However, energy justice scholars and activists have taken much interest in the distributional disparities evident in residential solar adoption and there is also growing interest in understanding how to expand solar adoption in underrepresented market segments [4–6]. It has long been recognized that solar adoption growth has not been equitably distributed across household income classes. Higher-income households represent a greater share of solar adopters than their share in the population. In a study of four states, California, New Jersey, Massachusetts, and New York, representing 65% of all residential PV installations, nearly 90% of installations were on houses with annual incomes of $45,000 or greater [7]. Households earning less than $45,000 annually were just 13% of PV installations, yet represented 25% of the total population [7].

In response to these disparities, state and local governments have recently developed programs, primarily focused on low- to moderate-income (LMI) households, in support of solar adoption parity. The combination of efforts by public agencies and firms to place special emphasis on targeting LMI households with declining PV costs, growth in third-party ownership models, solar market maturity and customer awareness, and a larger number of firms seeking customer expansion, has helped trend the median household income for residential PV adoption downward. Since 2010, the median household

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income for PV adopters dropped from $100,000 to $87,000 in 2016 [8].

Many treatments on the topic of expanding solar access to LMI households have focused on the economic models that can overcome the barrier of high upfront costs of solar for resource-strapped households [9–11]. One cost-saving measure and means to increase solar participation is simply better understanding the distribution of the LMI solar market itself. For instance, knowing how many households could be targeted and exactly where those rooftops are located. The merging of new national datasets that estimate rooftop potential and rooftop solar penetration with socioeconomic and demographic data from the United States Census provide the opportunity to delve deeper into understanding solar disparities which may enhance local policy development and implementation.

Thus, this paper sought to answer three questions. First, how are spatial distributions of rooftop potential and penetration similar and different across cities? Second, how is rooftop penetration distributed across non-LMI and LMI communities in different cities? Third, how do the relationships between rooftop penetration and local socioeconomic and demographic characteristics, identified as barriers to solar adoption, differ? These questions were explored across four United States cities – Riverside and San Bernardino, California, Washington, D.C., and Chicago, Illinois – to understand both universal and distinct local manifestations. These cities were chosen based on being geographically dispersed across the country, at varying maturations in their LMI solar policies and programs, and diversity in their size, population, demographics, socioeconomics, and residential solar potential and penetration estimates.

1.1. Other barriers to LMI solar adoption

Research comparing LMI and high-income PV adopters finds they are more alike than not, both fitting pro-environmental profiles, drawn to novel technologies, and motivated to adopt solar in order to save money [12]. Thus, demonstrating that the socioeconomic disparities evident in PV adoption are not because of a lack of desire to adopt, but may exist due to other preventive barriers. Thus, scholars have sought to understand the environmental, social, and economic variables that influence residential PV deployment, finding that over and underperforming areas have significant relationships, beyond income, with race/ethnicity, education, age and political ideology [13]. Again, recent data advances in solar installation tracking have allowed even greater analyses of PV deployment disparities. For instance, large racial and ethnic disparities in solar deployment have become apparent. Sunter et al. found significant racial disparities in solar deployment, even after accounting for household income and home ownership, finding that majority black or Hispanic census tracts had 69% and 30%, respectively, less solar installed, while white majority tracts had 21% more solar, when compared to tracts with no racial/ethnic majority [14].

One challenge is reaching underrepresented communities to convey the benefits of solar. A review of nontechnical barriers by the National Renewable Energy Lab found the lack of information dissemination and consumer awareness about renewable energy was the second most prevalent barrier to solar adoption following the lack of supportive government policy [15]. One avenue to reach households is through the internet; however, LMI households are more likely to be without internet access (30%) compared to higher-income households (20%) [16]. Another challenge to solar information dissemination and shown to be associated with reduced solar adoption in LMI communities is limited English proficiency [17]. There are over 25 million residents in the United States who do not speak English as their primary language and have a limited ability to read, speak, write or understand English [18]. Limited English proficiency has been shown to be an impediment to environmental participation and decision making, and can have profound, long-term ramifications, increasing household vulnerability [18].

The split-incentive challenge, a well-known principal-agent problem, has been well-studied in the energy efficiency literature [19,20], and is also relevant for reducing solar adoption disparities. The split-incentives challenge is "a circumstance in which the flow of investments and benefits are not properly rationed among the parties to a transaction, imparting investment decisions" [21]. LMI households are more likely to rent, by which the property owner, or landlord, who would be responsible for the cost of energy-related improvements has no incentive to do so, as they will not realize the immediate benefits. This is important when considering that 75% of renter-occupied households pay all energy costs directly, meaning neither heat nor electricity is paid by the landlord, according to data from the 2015 Residential Energy Consumption Survey. Thus, for private landlords, making solar investments is an unprofitable proposition. The split-incentive barrier is an especially acute challenge in communities where there is a concentration of privately-owned, low-income rental housing.

1.2. Solar equity policies and case study cities

Several states in the United States have been at the forefront of developing polices and mechanisms to expand solar to underrepresented households and communities, focused primarily on LMI households and often motivated by three primary objectives: reduce overall energy demand; reduce household energy burdens; and job creation. In lower-income urban areas, higher housing density, historically, has resulted in reduced adoption rates of renewables [4]. State and local politics and governance have tremendous influence over the prospects of solar growth within their boundaries [13]. Thus, it is important to assess solar dynamics at both the state and local levels. Additionally, local organizations and governments have the ability to recognize the unique challenges and characteristics of their cities and act accordingly to find solutions to barriers as they arise [19]. Therefore, an understanding of local characteristics is important for visualizing the spatial nuances that may either hinder or facilitate LMI solar expansion.

Most solar equity policies define LMI households or communities as those with annual earnings 80% or less of the Area Median Income (AMI), adjusted for the total number of household members. This definition of LMI is used by the US Department of Housing and Urban Development (HUD) and is the preferred definition across many assistance programs as opposed to Federal Poverty Level (FPL). AMI is more sensitive to income level variations across geographic areas (e.g., counties), while FPL is set uniformly to national averages. The costs of LMI solar programs are covered by a variety of sources, such as, federal, state, and local incentives, utility or ratepayer funds, philanthropic grants and donations. This section briefly describes LMI solar legislation and programs in California, Washington, DC and Illinois and the context for the four local case studies.

In 2006, the State of California created the California Solar Initiative (CSI) as a solar rebate program for customers of the state's investor-owned utilities (IOUs) – Pacific Gas and Electric (PG&E), Southern California Edison (SCE), and San Diego Gas and Electric (SDG&E). The CSI includes the Single-family Affordable Solar Homes (SASH) program targeting low-income households. The SASH program began with $162 million in incentives, was extended in 2013 until 2021 with an additional $54 million in new funding. A new SASH program for disadvantage communities, DAC-SASH, will specifically target single-family homes in environmental justice communities. In California, the cities of Riverside and San Bernardino are the focus for this study. Riverside and San Bernardino are neighboring cities in California's Inland Empire region and part of the Riverside-San Bernardino-Ontario, CA metropolitan statistical area (MSA). MSAs are the formal definition of a region that consists of a city and surrounding communities that are linked by social and economic factors, as established by the United States Office of Management and Budget (OMB). The region is one of the fastest growing in the state and 13th largest metropolitan area in the United States as more people leave Los Angeles seeking affordable housing. Of interest for this study is that while the cities are close in proximity, in the same MSA, they are served by different electric utilities which has implications for household access to LMI solar incentive programs. While LMI households in San Bernardino may participate in the SASH program because they receive electricity from SCE, LMI households in Riverside are ineligible to participate in the SASH program because the city operates its own municipal utility and does not offer special solar incentives for LMI households. This exercise allows for a proximate visualization of the potential importance of solar equity programs in increasing parity. All else being equal, we would expect to see higher solar penetration in LMI communities in San Bernardino than in Riverside. The California SASH program launched in 2009.

Washington, DC is the capital of the United States and the first Leadership in Energy and Environmental Design (LEED) Platinum city. A designation by the United States Green Building Council to recognize the outcomes, rather than intent, of the city's leadership in creating a sustainable and resilient built environment, which include: reducing greenhouse gas emissions, supporting clean energy innovation, and focusing on inclusive prosperity and livability. In 2016, Washington, DC passed the Renewable Portfolio Standard Expansion Amendment Act (D.C. Law 21-154; 63 DCR 12926) which established the Solar for All Program. The Solar for All Program is funded by the Renewable Energy Development Fund (REDF), a law mandating alternative compliance payments levied against utility companies that fail to meet the District's renewable portfolio standard and administered by the city's Department of Energy & Environment (DOEE). The Solar for All program's goal is to provide solar electricity to 100,000 low-income households (households at or below 80% Area Median Income) and to reduce energy bills by 50% by 2032. Prior to establishing the Solar for All program, Washington, DC launched two pilot programs installing nearly 350 PV systems on LMI rooftops. In 2012 the Small-Scale Solar Initiative completed 54 LMI installations [22]. In 2015 and 2016, the Solar Advantage Plus program completed 295 installations [23]. The Washington, DC Solar for All program launched in 2017.

In 2007, the State of Illinois passed the Illinois Power Agency Act (20 ILCS 3855) creating the Illinois Power Agency tasked with developing the Illinois Solar for All Program. The Solar for All program includes incentives for low-income distributed generation and community solar projects. In 2016, Illinois passed the Future Energy Jobs Act (FEJA), (Public Act 99-0906) which revamped the state's Renewable Portfolio Standard and committed $750 million in funding to expand the Solar for All program through: (1) low-income distributed generation incentive; (2) low-income community solar project initiatives; (3) incentives for non-profits and public facilities; and (4) low-income community solar pilot projects. The low-income distributed generation incentive program provides incentives to increase participation of low-income households in on-site PV generation. An additional goal of the Solar for All program is that at least 25% of the incentives are allocated to projects in environmental justice communities, defined as communities with low income and minority populations greater than twice the state average and are geographic locations that potentially experience disproportionate environmental harms and risks. For this study, Chicago, Illinois , the largest city in the state and this study, and third most populous city in the US is the focus. Chicago has pledged a goal of being 100% renewable by 2035. The Illinois Solar for All program launched in 2019.

Table 1 presents the socioeconomic and demographic characteristics of the case study cities.

2. Materials and methods

This research utilized three publicly available data sources: the National Renewable Energy Lab's (NREL) Rooftop Energy Potential of Low-income Communities in America (REPLICA);[1] Stanford University's DeepSolar; [2]and the United States Census Bureau's American Community Survey (ACS, 2011–2015, 5-year).

First, the REPLICA dataset provides census tract-level estimates of residential rooftop solar potential, with a special emphasis on low- to moderate-income potential, and provides an estimate of the number of solar suitable rooftops determined by rooftop shading, azimuth, tilt, and a minimum 10 m^2 area [24]. According to REPLICA, the majority of estimated residential rooftop potential (68.4%) in the United States was on single-family dwellings (61.8 million rooftops), and exceeds multi-family rooftop potential across all income groups, with an estimated annual generating potential of 683TWh, compared to 316TWh for multi-family dwellings [25]. LMI-occupied households represented 37% of all solar suitable single-family rooftops [25]. The model year vintage of REPLICA is 2015.

Second, DeepSolar, a national solar deployment database provides estimates of the number of installed residential PV systems at the census tract-level. DeepSolar uses a machine learning framework to analyze satellite imagery for identifying locations and sizes of PV panels [26]. DeepSolar estimated approximately 1.28 million residential PV systems in the contiguous United States The model year vintage of DeepSolar is 2015.

Third, the United States Census Bureau's American Community Survey (ACS, 2011–2015, 5-year) provides census tract-level estimates of socioeconomic, demographic, and housing characteristics. The ACS is a small-sample survey conducted between decennial census surveys to provide 1-, 3- and 5-year rolling estimates. The 5-year ACS estimates are based on larger survey samples, and thus considered more reliable.

The REPLICA, DeepSolar and ACS datasets were merged by matching census tract geographic identifiers (GEOIDs), which are numeric codes that uniquely identify all administrative/legal and statistical geographic areas for which the United States Census Bureau tabulates data. Next, four variables were calculated for each census tract in the four cities: total rooftop potential; LMI rooftop potential; LMI market share; and total rooftop penetration. *Total rooftop potential* is the proportion of single-family rooftops that are solar suitable estimated in the REPLICA. For each census tract, *total rooftop potential* was calculated by dividing the total number of solar suitable single-family dwellings by the total number of single-family dwellings. *LMI rooftop potential* is the proportion of LMI-occupied single-family rooftops that are solar suitable estimated in the REPLICA. For each census tract, *LMI rooftop potential* was calculated by dividing the number of LMI-occupied solar suitable single-family dwellings by the total number of LMI-occupied single-family dwellings. *LMI market share* is the proportion of solar suitable single-family rooftops that are LMI-occupied estimated in the REPLICA. For each census tract, *LMI market share* was calculated by dividing the number of LMI-occupied solar suitable single-family dwellings by the total number of solar suitable single-family dwellings. *Total rooftop penetration* is the proportion of solar suitable single-family dwellings

[1] https://maps.nrel.gov/solar-for-all/
[2] http://web.stanford.edu/group/deepsolar/home

Table 1
Socioeconomic and demographic characteristics of case study cities.

	Riverside, CA	San Bernardino, CA	Washington, DC	Chicago, IL
Low-Income Solar Program (Year Launched)	None	Single-family Affordable Solar Homes (SASH) (2009)	Solar for All (2017)	Solar for All (2019)
Total population	316,335	214,112	647,484	2,717,534
Non-white population	33.6%	44.6%	59.8%	51.3%
Population 65 or older	9.8%	8.3%	11.3%	10.9%
Limited English proficiency	5.9%	10.2%	3.2%	8.9%
Less than high school education	21.5%	20.7%	10.7%	17.7%
Low- to Moderate-Income Limit (*80% AMI for family of 4* [a])	$49,700	$49,700	$68,000	$60,800
Renter-occupied housing	44.7%	53.1%	58.8%	55.7%
Households without internet	12.6%	21.2%	17.5%	20.6%
Median home value	$261,400	$159,800	$475,800	$222,900

Source: United States Census Bureau, 2011–2015 American Community Survey 5-Year Estimates.
[a]US Department of Housing and Urban Development, FY 2015 Income Limits Summary.

with solar. For each census tract, *total rooftop penetration* was calculated by dividing the total number of residential solar systems estimated by DeepSolar, by the total number of solar suitable single-family dwellings estimated by REPLICA.

Estimates for the four variables, reported as percentages for each city, are shown in Table 2. Riverside and San Bernardino had the highest, and relatively similar, total rooftop potential (84% and 85% respectively). In all four cities the proportion of LMI rooftops that were solar suitable (LMI potential) was similar to total rooftop potential, demonstrating that on average, and based on the REPLICA criteria, LMI single-family rooftops were no more or less solar suitable than non-LMI single-family rooftops. In San Bernardino the LMI market share represented more than half (51%) of the solar suitable rooftops, followed by Chicago with just under half (46%), and both San Bernardino and Washington, DC with just over one-third (35% and 34%, respectively). Although Washington, DC had the lowest total rooftop potential and LMI rooftop potential of the four cities (both 16%), the LMI market share was more than double (34%) the rooftop potential and the city also had the highest total rooftop penetration (12%) of the four cities. Chicago on the other hand, with more than half (55%) of its single-family dwellings estimated as solar suitable had the lowest total rooftop penetration of all four cities, only 0.3%.

Table 2
Citywide descriptive statistics.

	Riverside	San Bernardino	Washington, DC	Chicago
Total single-family rooftops [a]	84,675	63,666	101,933	462,013
Total solar suitable rooftops [a]	70,957	54,080	16,151	254,200
Total rooftop potential	84%	85%	16%	55%
Total LMI single-family rooftops [a]	30,390	32,862	33,130	204,397
LMI solar suitable rooftops [a]	24,868	27,457	5,426	117,949
LMI rooftop potential	82%	84%	16%	58%
LMI market share	35%	51%	34%	46%
Total rooftops with solar [b]	4,890	4,122	2,000	881
Total rooftop penetration	7%	8%	12%	0.3%

Sources: a. REPLICA; b. DeepSolar.

Table 3 presents descriptive statistics at the census tract level. The number of census tracts and the proportion that are inhabited by a majority of LMI households varied across the cities. In Washington, DC 27% of the census tracts are LMI-majority, while 55% of the census tracts in San Bernardino are LMI-majority. Total rooftop potential for census tracts in Riverside ranged from 31% to 92%, 54% to 93% in San Bernardino, 0.5% to 35% in Washington, DC and 0.1% to 90% in Chicago. LMI rooftop potential ranges for census tracts in Riverside, San Bernardino, and Washington, DC were the same as total rooftop potential, and 0% to 91% in Chicago. LMI market share for census tracts in Riverside ranged from 7% to 83%, 12% to 90% in San Bernardino, 4% to 87% in Washington, DC and 0% to 94% in Chicago. Total rooftop penetration for census tracts in Riverside ranged from 0.8% to 28%, 0.7% to 39% in San Bernardino, 0.5% to 35% in Washington, DC and 0% to 100% in Chicago.

First, using geographic information systems (GIS) software, the distributions of total rooftop potential, LMI market share, and total rooftop penetration were mapped to visually compare and contrast low- and high-levels of each across the four cities. Next, to examine the relationships between rooftop penetration between LMI and non-LMI communities, bivariate analyses (ANOVA) were conducted across LMI market share quintiles in each city.

Lastly, to further explore the relationships between solar penetration and area-level socioeconomic and demographic characteristics that may be associated with more or less solar penetration four regression models were developed. The dependent variable was census tract-level solar penetration (from DeepSolar), and the 12 independent variables included two variables from REPLICA: total rooftop potential estimates; and LMI market share, and nine socioeconomic, demographic obtained from the ACS: proportion of renter-occupied households; limited English proficiency; population with less than a high school education; population age 65 or older; race/ethnicity; households without internet; dwellings built in the 2000s; dwellings built before 1960; median household income; and median home

Table 3
Census tract-level descriptive statistics.

	Riverside	San Bernardino	Washington, DC	Chicago
Census tracts	76	58	172	782
LMI-majority census tracts [a]	15 (20%)	32 (55%)	47 (27%)	385 (49%)
Total rooftop potential, % mean (SD)	83.5 (8.9)	84.8 (6.0)	18.1 (10.6)	60.9 (25.5)
LMI rooftop potential, % mean (SD)	82.9 (8.9)	84.5 (6.0)	16.8 (10.3)	60.4 (25.4)
LMI market share, % mean (SD)	38.2 (15.7)	53.5 (18.3)	35.3 (20.8)	49.1 (19.0)
Total rooftop penetration, % mean (SD)	6.1 (5.6)	6.9 (6.3)	18.0 (17.7)	1.5 (8.6)

a. Census tracts where greater than 50% of single-family dwellings are LMI-occupied.

value. It is important to note that the dependent variable, total rooftop penetration, was natural logged to better fit the nonlinear relationship between rooftop potential and the independent variables. All statistical analyses were performed using Stata version 15.1. All mapping analyses were performed using ArcGIS version 10.5.1.

3. Results

3.1. The relationship between total rooftop potential, LMI rooftop potential, and LMI market share

The spatial distribution of total rooftop potential, LMI market share, and total rooftop penetration are shown in Fig. 1. The first panel (from the left) illustrates the location of each city and the legend. Census tract-level rooftop potential, LMI market share and penetration are divided into quintiles, with census tracts in lowest quintile in the lightest shading and census tracts in the highest quintile in the darkest shading. The second panel contains the city names. The third panel illustrates the spatial distribution of total rooftop potential. The fourth panel illustrates LMI market share. Lastly, the fifth panel illustrates total rooftop penetration (which will be discussed in the next section).

In all four cities, higher levels of total rooftop potential are in census tracts surrounding the central city, or urban core, where a greater number of suburban neighborhoods with larger single-family dwellings are located in contrast with more dense neighborhoods of smaller single-family homes in the urban core. As seen in Tables 2 and 3, total rooftop potential and LMI rooftop potential (not mapped) are similar in each city and statistically correlated ($p < 0.001$); 0.99 in Riverside and San Bernardino, 0.97 in Washington, DC, and 1.0 in Chicago.

Census tracts with the greatest proportion of solar suitable rooftops on LMI single-family homes (or the highest LMI market share) are generally spatially clustered in each city, such as, northeast Riverside, south San Bernardino, northeast Washington, DC, and south Chicago, corresponding with census tracts in parts of the city with the highest proportion of LMI occupied single-family dwellings. However, when we explore the relationship between rooftop potential (or the proportion of solar suitable homes), both total and LMI potential with LMI market share, we see inconsistent relationships. In Riverside and San Bernardino rooftop potential and LMI market share were negatively correlated, −0.41 and −0.46 ($p < 0.001$), respectively. Thus, census tracts with a higher proportion of the solar suitable rooftops being on LMI homes, were not necessarily the same census tracts where you would find the higher rooftop potential. However, a different relationship exists in Washington, DC and Chicago where rooftop potential and LMI market share are positively correlated, 0.26 and 0.21 ($p < 0.001$), respectively. Thus, in Washington, DC and Chicago, some census tracts where LMI-occupied homes represent a greater share of the solar suitable rooftops, are also ones with higher rooftop potential. Therefore, the notion that LMI communities have lower rooftop potential is not universally true.

3.2. The relationship between LMI market share and rooftop penetration

To explore the relationship between LMI market share and rooftop penetration, visualized in Fig. 1, ANOVA results for total rooftop penetration across the quintiles of increasing LMI market share are illustrated in Fig. 2 for each city. Since negative relationships between rooftop potential and LMI market share existed in Riverside and San Bernardino, it is probable that rooftop penetration would be lower in census tract in higher quintiles of LMI market share, as census tracts with higher potential and higher incomes would be targeted by solar installers. Further, since San Bernardino is served by the SASH LMI solar program and Riverside is not, it is probable to expect higher penetration rates in LMI census tracts in San Bernardino than in Riverside. In Washington, DC and Chicago where the relationship between rooftop potential and LMI market share were positive, it is probable that areas with higher LMI market share could have similar or higher penetration rates than census tracts with lower LMI market share.

In both Riverside and San Bernardino, average rooftop penetrations were near 15% in census tracts in the lowest LMI market share quintile and were significantly higher than all other quintiles in Riverside ($F(4,71) = 28.9$, $p < 0.001$) and significantly higher than the third, fourth and fifth quintiles in San Bernardino ($F(3,53) = 10.5$, $p < 0.001$). In Washington, DC, on average, rooftop penetration exceeded 20% in census tracts in the lowest three quintiles. However, only the second and fifth quintiles had statistically significantly different penetration means ($F(4, 171) = 3.8$, $p < 0.01$). Lastly, mean rooftop penetration in Chicago was relatively low across LMI market share quintiles when compared to the other three cities. Rooftop penetration in census tracts in the lowest LMI market share quintile averaged 3.2% and was only statistically higher than census tracts in the fourth quintile which had an average 0.4% rooftop penetration ($F(4, 781) = 2.3$, $p < 0.1$). While in Fig. 1 it appeared a select few census tracts with high LMI market share also exhibited high rooftop penetration, on average, higher mean rooftop penetrations were statistically associated with census tracts with a lower proportion of solar suitable rooftops occupied by LMI households (or LMI market share).

The similar penetration pattern in Riverside and San Bernardino is particularly interesting. Considering that LMI households in San Bernardino benefit from the state-sponsored SASH program, while LMI households in Riverside do not, it would be expected that higher penetration rates might exist in San Bernardino census tracts with larger LMI market share. ANOVA results for both LMI rooftop potential and penetration in LMI demonstrated no statistical differences in mean penetration between the two cities. However, we do see higher mean rooftop penetrations in quintiles 2, 3 and 4 in San Bernardino when compared to the same quintiles in Riverside. Moreover, it is important to understand whether income remains the primary barrier to rooftop solar adoption across census tracts and how income as well as other socioeconomic and demographic characteristics are associated with penetration across the four cities.

3.3. The relationship between rooftop penetration and socioeconomic and demographic characteristics

Results for regression models examining the relationship between rooftop penetration and census-tract level demographic and socioeconomic variables are shown in Table 4. The Riverside model shows that three variables had a statistically significant relationship with rooftop penetration: percentage of homes without internet; percentage of homes built before 1960; and median home value. A 10% increase in households without internet access, and houses built before 1960 was associated with a 33% and 7% reduction in rooftop penetration, respectively.[3] Home value was positively associated with roof penetration, where a $10,000 increase in median home value saw a 4% increase in rooftop penetration

In San Bernardino, two variables were associated with lower rooftop penetration. A 10% increase in LMI market share and limited English proficiency were both associated with a 36% decrease in rooftop penetration. Three variables were associated with higher

[3] To interpret the regression results from a model with a logged dependent variable the coefficient is exponentiated, for example, for a 10% increase in homes without internet, since $\exp(-0.040 \times 10) = 0.67$; and $0.67–1 = –0.33$ or –33%.

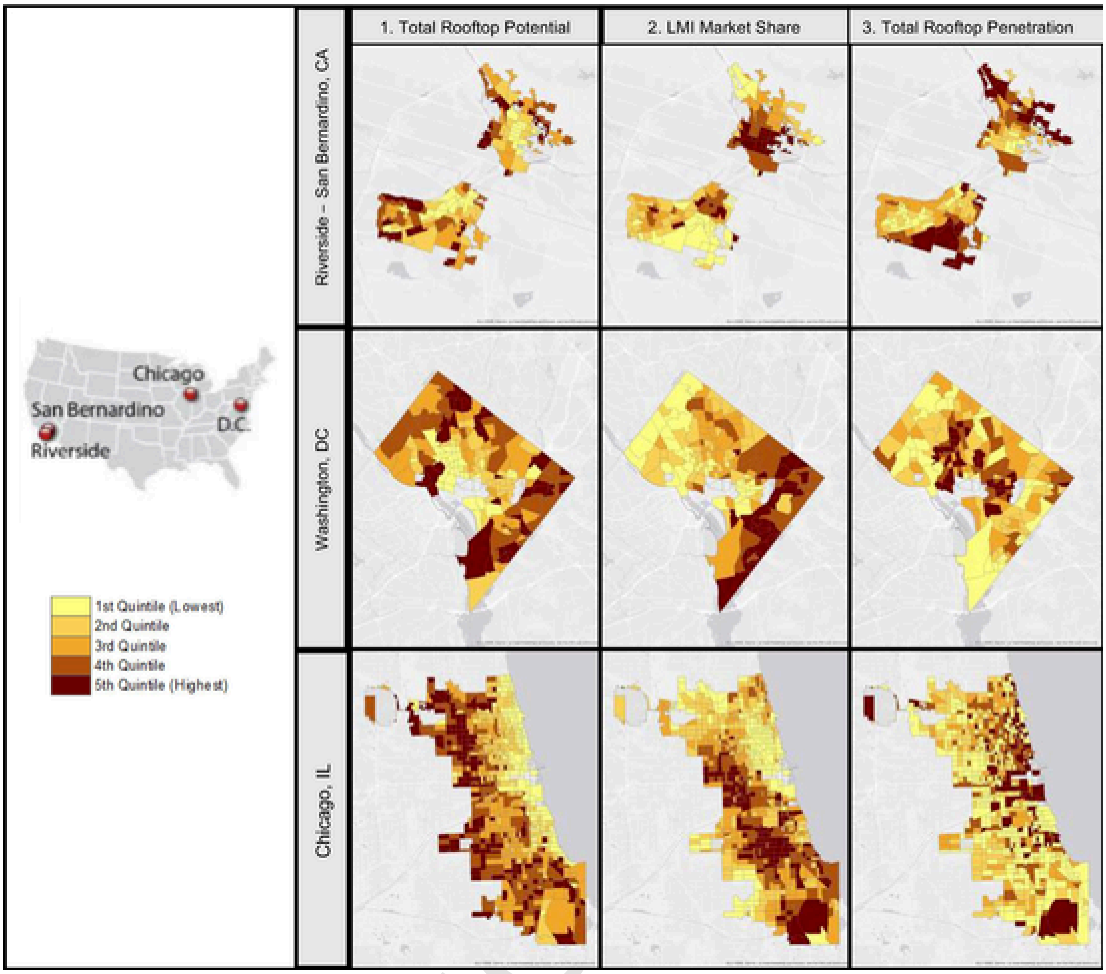

Fig. 1. Quintile spatial distribution of census tract-level (1) total rooftop potential (proportion of rooftops that are solar suitable), (2) LMI market share (proportion of solar suitable rooftops that are LMI-occupied), and (3) total rooftop penetration (proportion of solar suitable rooftops with solar).

rooftop penetration. A 10% increase in both the population with less than high school education and 65 or older was associated with a 39% increase in rooftop penetration, while a 10% increase in nonwhite population was associated with a 21% increase in rooftop penetration.

In Washington, DC, three variables had a significant negative relationship with lower rooftop penetration. A 10% increase in total rooftop potential was associated with 34% lower rooftop penetration, while a 10% increase in LMI market share was associated with 22% lower rooftop penetration. A 10% increase in the percentage of the population 65 or older was associated with 25% lower rooftop penetration.

In Chicago, two variables had a statistically significant relationship with rooftop penetration. A 10% increase in total rooftop potential was associated with 25% lower rooftop penetration, and a 10% increase in newer homes, built in 2000 or later, was associated with 25% higher rooftop penetration.

4. Discussion

Solar potential not only differs across cities, but also across communities within a city. As efforts to improve solar adoption parity expand, it is important to understand the rooftop market potential. Contrary to conventional wisdom, the highest rooftop solar potential is not always or only in the highest income neighborhoods in a city. Rooftop potential was relatively high across all LMI quintiles in Riverside and San Bernardino, approaching or surpassing 80%. In both Washington, D.C. and Chicago, the highest rooftop potential was not found in the highest income neighborhoods, but rather located in census tracts with higher percentages of LMI households. Thus, with LMI homes representing more than 1/3 of the solar suitable homes in Riverside and Washington, DC, and 46% and 51% in Chicago and San Bernardino, respectively, lower penetration of solar in LMI communities substantially reduces the overall attainment of renewable energy and energy equity goals in these cities.

Rooftop penetration rates varied greatly across the four cities, and was relatively low. Surprisingly, Washington, D.C. had higher rooftop penetration rates than the other three cities. However, the pattern of solar penetration was less varied across the cities. In all four cities higher rooftop penetration was unsurprisingly associated with higher-income census tracts. The comparison between Riverside, which has no LMI solar incentive program, and its neighbor San Bernardino, which is covered by California's LMI SASH program, is interesting in that, all else being equal we would expect higher penetration rates in LMI potential quintiles in San Bernardino. On the contrary, census tracts in the highest LMI potential quintiles in both cities had nearly the same mean penetration rate. On the other hand, there was higher mean penetration in census tracts in the second, third and fourth LMI quintiles in San Bernardino than Riverside. Because this study evaluates area-based potential and penetration, it is impossible to know if installations in high-LMI potential areas actually occurred on LMI rooftops. Thus, to fully determine the impact of LMI policies on LMI adoption, additional data and analyses are nec-

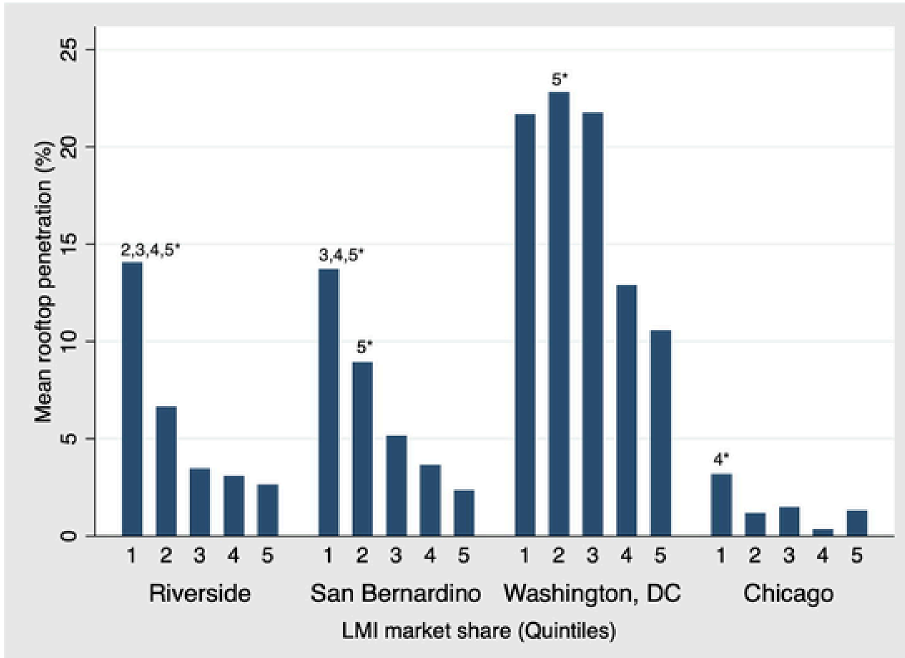

Fig. 2. Distribution of mean rooftop solar penetration across census tracts categorized by LMI market share quintiles for each city, where 1 = lowest LMI market share quintile and 5 = highest LMI market share quintile. These quintiles correspond with those in Fig. 1. Numbers above bar indicate groups with statistically significant differences based on Bonferroni multiple-comparison test, $p < 0.05$.

Table 4
Regression results between total rooftop penetration and socioeconomic and demographic variables.

	Riverside		San Bernardino		Washington, DC		Chicago	
	b	S.E	b	S.E	b	S.E	b	S.E
Total rooftop potential (%)	0.010	0.008	−0.002	0.012	−0.042*	0.008	−0.029*	0.003
LMI market share (%)	−0.005	0.016	−0.044*	0.016	−0.025*	0.011	0.002	0.011
Renter-occupied housing (%)	−0.016	0.046	0.004	0.045	0.025	0.030	−0.031	0.028
% Limited English proficiency	−0.012	0.018	−0.044*	0.016	−0.020	0.017	−0.010	0.008
% Population w/less than high school education	0.008	0.008	0.033*	0.009	0.023	0.016	−0.001	0.007
% Population 65 or older	0.013	0.016	0.033*	0.017	−0.029*	0.013	0.011	0.010
% Nonwhite population	0.001	0.007	0.019*	0.008	0.003	0.005	−0.002	0.002
% Households w/o internet	−0.040*	0.014	−0.023	0.014	−0.013	0.010	−0.004	0.008
% Homes built in 2000 or later	0.000	0.005	−0.014	0.011	0.004	0.006	0.022*	0.009
% Homes built before 1960	−0.007*	0.004	0.003	0.003	0.007	0.005	−0.003	0.003
Median household income ($)	−0.002	0.011	−0.004	0.015	−0.003	0.004	−0.003	0.005
Median home value ($)	0.004*	0.002	0.004	0.002	0.000	0.000	0.000	0.001
Constant	0.836	1.569	2.164	2.344	3.552*	0.69	1.277	0.793
N	75		57		163		405	
R^2	0.70		0.78		0.45		0.55	

*Significant at the 0.1 level.

essary. However, this analysis does indicate higher average rooftop penetration in LMI communities in San Bernardino when compared to Riverside, although these means are not statistically different.

This study also highlights that in some cities there is a mismatch between rooftop potential and penetration. In Washington, D.C. and Chicago, although the highest mean potential was in LMI census tracts, that did not translate into higher penetration. Washington, D.C. and Chicago are younger in their pursuits of solar equity, with Solar For All programs launching in 2017 and 2019, respectively. Since the rooftop penetration data used in this study is from 2015, it will be important to update this type of analysis in the future to explore changes in the distribution of rooftop penetration. Interestingly, although Chicago had had the lowest penetration rates of the four cities, in the regression model LMI rooftop potential was associated with an increase in penetration. This may be associated with the fact that in in 2012 the City and its local utility were awarded a grant from the United States Department of Energy to reduce market barriers and support rooftop solar and later in 2014 the Solar Chicago program launched to make available affordable rooftop solar funding.

The lack of internet access was negatively associated with rooftop penetration in the Riverside regression model. One approach to overcome the lack of internet access barrier to information dissemination that has worked in LMI energy efficiency expansion is to employ community-based approaches to sharing information [19]. Low-income solar program managers have identified community solar meetings or workshops held at local community centers or churches as a prime opportunity to gather multiple households that are potentially interested in or would benefit from solar. Sharing information with multiple families in one location may be a more efficient use of time and may also increases the opportunity for information to spread within a geographic location. For instance, meeting attendees are equipped with first-hand information that they can then share with neighbors or other households that were not in attendance. Another approach is on-the-ground outreach in target communities such as door-to-door information canvasing. This allows for more personal, one-on-one information sharing, and potentially increases the chances of obtaining necessary information to commence the solar adoption process.

Negative relationships between racial/ethnic minorities and solar penetration has been found in other studies on solar deployment in the United States [14]. Black and Hispanic households are disproportionally more likely to rent when compared to White and Asian households, which as mentioned earlier, renter-occupied dwellings are correlated with reduced PV penetration. Moreover, Black and Hispanic median household incomes are 2/3 and 3/4, respectively, the median household income for whites. Therefore, in general Black and Hispanic households are less likely to have rooftop solar when compared to White and Asian households. The disparities in solar adoption across race and ethnicity can be framed as recognition injustice or the lack of recognizing the unique needs of particular social groups [27,28]. Recognition of communities disproportionately impacted by energy dynamics, sometimes known as "energy sacrifice zones" [29] should receive deliberate attention in the design and deployment of energy policies that promote the transition to cleaner and renewable energy sources. However, it should be noted that in this study the percent nonwhite population in San Bernardino was actually positively associated with penetration, which corresponds with the city being majority nonwhite (nearly 85% nonwhite, 65% Hispanic). In the three other cities, there was no statistically significant relationship between race/ethnicity and solar penetration.

There are positive developments in California and Illinois intended to correct solar recognition injustice and expand solar targeting and benefits beyond simple income-based measures to include racial and ethnic disparities, and disproportional environmental burdens. California Senate Bill 350 (SB350), known as the Clean Energy and Pollution Reduction Act of 2015, necessitated the creation of a Disadvantaged Communities Advisory Group (DACAG) to advise programs on how to best implement clean energy and pollution reduction in *disadvantage communities*. The bill purports that programs should commit to outreach activities that inform disadvantaged communities about the opportunities to take part in state solar programs. Disadvantaged communities are: "areas disproportionately affected by environmental pollution and other hazards that can lead to negative public health effects, exposure, or environmental degradation; and areas with concentrations of people that are of low-income, high unemployment, low levels of home ownership, high rent burden, sensitive populations, or low levels of educational attainment" [30].

As mentioned earlier, a primary goal of the Illinois Solar for All program is that a minimum of 25% of incentives be allocated to projects located within *environmental justice communities*. The State recognizes that environmental justice as a multi-faceted issue with multiple indicators that can be used to define an environmental justice community. In defining environmental justice communities, the primary factors considered by the State are, income, race/ethnicity, other demographic characteristics, and environmental impacts (i.e. pollution). Disadvantaged or environmental justice community designations, serve to not only recognize the patterns by which cities have developed over time, but also a host of distributional inequalities (i.e. pollution, income, health). Rather than allowing the exclusion of communities in the clean energy transition, they become primary targets for clean energy investment.

5. Conclusion

The growth in solar adoption in the United States over the last decade has not occurred equitably across socioeconomic groups. LMI households and communities are more likely to experience lower rooftop penetration rates compared to higher income households and communities. State and local governments are implementing solar equity policies and programs with hopes to improve parity. This study combines national datasets that estimate rooftop solar potential, penetration, and socioeconomic and demographic characteristics to explore the distributional disparities within and across four cities in the United States. Higher rooftop potential is not always found in higher income communities. Higher potential does not necessarily translate to higher penetration, especially if higher potential was in LMI communities. While the proportion of LMI solar suitable rooftops was associated with the level of solar penetration, other socioeconomic and demographic factors such as race/ethnicity, limited English proficiency, age of housing stock, and internet access, were also associated with penetration rates, variably across cities. Nevertheless, there remains great potential for expanding rooftop solar to LMI households and communities for which only a fraction of the market has been reached. Recognizing the distributional disparities in rooftop potential and penetration and taking into consideration the unique socioeconomic and demographic characteristics of cities will allow for a more holistic understanding of the local LMI solar market. This knowledge will lead to better policy design and program implementation. While many lessons have been learned in the development and implementation of LMI solar programs over the last decade, there remains room for improvement. Future research is needed to track the progress of newer solar equity polices and identify remaining barriers, beyond costs, as programs mature.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2020.101612.

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