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City living but still energy poor: Household energy transitions under rapid urbanization in Myanmar

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ABSTRACT

Do energy transitions co-evolve with urbanization? We examine energy access in rapidly urbanizing Yangon, Myanmar using a two-wave mixed-method observational study design involving households (N = 600) situated along a rural to urban gradient. Heterogeneity in urbanicity allows us to substitute space for time to understand energy transitions. We examine factors associated with access and reliability of grid infrastructure, and use of clean fuels. Qualitative interviews (N = 20) with urban households explore drivers and barriers of transitions to modern energy. We find substantial heterogeneity in urban grid access, ranging from 58% to 99%. Urban residents with 'informal' status have significantly lower odds of grid access (odds ratio (OR): 0.02, 95% confidence interval (CI), 0.00-0.34), and exclusive use of clean cooking fuels (OR: 0.17, 95% CI: 0.07-0.38). Informal and low-income households report energy access challenges due to lack of legal residency and cost of clean fuels. Urban energy poverty is persistent; households residing in Yangon for 5–10 years have significantly lower odds of using exclusive clean fuel for cooking (OR: 0.38, 95% CI: 0.24-0.60) and lighting (OR: 0.32, 95% CI: 0.13-0.79) compared to newer migrants. We find that despite lower grid access in rural areas adjacent to urban agglomerations, rural households are 2.6 to 6.5 times more likely to use clean lighting fuels due to high take-up of solar and more reliable grid electricity. We recommend future research on factors influencing heterogeneity of urban energy acccess, and that policy makers address barriers to energy transitions for marginalized urban populations.

1. Introduction

Energy access, energy poverty, and energy transitions in cities in low- and middle-income countries (LMICs) have received relatively little research attention. The general perception is that energy poverty primarily affects rural and remote populations, and that energy transitions including improvements in access to clean and affordable household energy occur in tandem with economic growth [1,2]. However, a significant number of urban residents have limited or no access to electricity, and clean cooking fuels and technologies [3-5]. As a result, millions of urban households are energy poor relying on inefficient technologies and dirty fuels, including kerosene and solid biomass fuels (e.g., charcoal, wood) for lighting, cooking and space heating.

Approximately 30% of people living in urban settings in low-income countries lack access to electricity [6]. In some sub-Saharan African countries, national averages for urban populations without access are as high as 60% [6]. Of the total 2.8 billion people without access to clean cooking, nearly half a billion or 17% of this population are urban residents [7]. The majority of the urban population without access to clean cooking facilities are in Asia and sub-Saharan Africa. China and India have the largest urban populations without access to clean cooking (147 million and 87 million people, respectively) [7]. Proportionally speaking, sub-Saharan Africa has the largest share (70%) of urban population without access to clean cooking [7].

Access to affordable and clean energy is recognized in one of the United Nations (UN) Sustainable Development Goals (SDG 7) [8]. Shifting away from use of biomass fuels with inefficient technologies can improve health outcomes [9-11], alleviate time burden particularly for women due to longer time spent cooking and collecting fuels [12], and reduce emissions of hazardous air pollutants [13]. Achieving SDG 7 would also provide co-benefits [11,14] for attaining other SDGs, including poverty reduction (SDG 1), promotion of health and well-

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being (SDG 3), gender equality (SDG 5), and climate action (SDG 13). In urban context, access to clean, affordable and safe energy also contributes to reducing inequalities (SDG 10) and promoting sustainable cities and communities (SDG 11).

Urban and rural comparisons of energy access in LMICs consistently suggests that energy poverty is more extreme in rural areas with a higher proportion of rural households lacking access to electricity and relying on biomass fuels for household energy services compared to urban areas [15-19]. Barriers commonly limiting rural energy transitions, such as geographical remoteness and sparse population [20], are not present in urban settings. Where access to modern fuels (e.g., solar or grid electricity or liquefied petroleum gas) exist, low cost and abundance of biomass fuels in rural areas make it difficult for households to transition; however urban areas are less likely to have the same access to biomass fuels. Further, urban households have been found to place more value on time savings compared to rural households [21], suggesting cleaner fuels and technologies that reduce cooking and fuel collection time may provide additional motivation for urban households to adopt modern fuels.

All this suggests that urbanizing communities or populations migrating from rural to urban areas would undergo a natural and relatively easy transition to clean energy. However, persistent use of wood, charcoal, dung, diesel, and other polluting fuels among urban populations in LMICs suggests a more complex picture. It contrasts with the energy ladder concept that higher household incomes associated with industrialization and urbanization lead to fuel switching from "primitive" biomass fuels to "advanced" fuels, such as electricity and LPG [22]. Several empirical studies suggest urban households engage in fuel "stacking" [23] where biomass fuels continued to be used in conjunction with modern fuels across developing Asia and sub-Saharan Africa [3,15,24-27].

Several studies have identified factors associated with urban energy poverty, including affordability, reliability, quality, availability, cultural preferences, and weather variability [4,5,26-29]. Energy poverty can be acute among urban low-income households who are unable to afford clean fuels and technologies [5,30] and where energy expenditures constitute a major component of household income [3]. This is not unlike challenges seen in rural settings where lower income households are less likely to adopt or switch completely to clean fuels and technologies [31,32]. Poorer households are also more sensitive to fuel price shocks than their wealthier counterparts [27], and may resort to cost minimizing behavior, such as reduced consumption.

A number of structural issues confound energy transitions in urban areas. Urban areas in LMICs can suffer from unreliable or low quality grid electricity leading to frequent blackouts and brownouts [29]. Supply and delivery infrastructure of modern fuels, such as LPG, can also influence clean fuel adoption in *peri*-urban and urban households [32,33]. For some urban populations, such as informal settlement households, accessing grid electricity may simply be not accessible due to "illegal" residential status [30,34]. In India, 4.5 million households in slums have no legal right to connect to the grid, entrenching the use of solid biomass for cooking, and kerosene for lighting [35].

Myanmar is a highly compelling place to study energy access in the context of rapid urbanization. Myanmar is one of the poorest countries in Southeast Asia with a quarter of the population living below national poverty line [36]. In the last decade, Myanmar has undergone major economic and political liberalization. From 2012 to 2018, Myanmar had one of the highest annual growth rates in gross domestic product per capita in Southeast Asia [37]. Between 2005 and 2017, the share of the population living below the national poverty line was reduced by half [36]. During the same period, significant energy transitions occurred. A comparison of 2014 and 2019 Census data indicate that solar and government- or community-based grid lighting grew by 234% and 64%, respectively, and cooking with grid electricity grew by 130% [38,39]. While the majority of the growth was in rural areas, urban areas also saw substantial growth with 17% in grid lighting, 93% in solar lighting, and 65% in grid supported cooking. In 2015, the National Electrification Plan (NEP) was announced with an objective of electrifying all households in Myanmar by 2030 (World Bank 2014). The combination of low but growing incomes, rapid urbanization and ambitious energy policy provides a relevant and significant context to study energy transitions and its' challenges in Myanmar.

Our study takes place in Greater Yangon City, located within Yangon Region, and is the largest city in Myanmar with a population of 5.16 million, or 35% of the country's urban population [37]. Population projections indicate that Yangon City will exceed 10 million by 2040 [40], earning a mega-city status. The majority of the population growth of Yangon is occurring in the outskirts of Yangon City, in satellite townships that were established in the 1980s to ease population density in the downtown region [41]. In the past decade, establishment of manufacturing and service industries [42] in the satellite townships have attracted large numbers of migrants to the city [40,43,44].

In this paper, we explore the structural and social determinants of energy access and energy poverty in Yangon's current and future satellite townships. Our study takes place in a rapidly urbanizing satellite township, Hlaingtharya, and the rural township of Htantabin, immediately adjacent to Hlaingtharya. Htantabin is very likely to become a satellite/urban township in the very near future. Our research questions are: 1) What is the state of access to modern energy services for cooking and lighting in Yangon's rapidly urbanizing township and adjacent rural areas?; and 2) What factors influence household access to modern energy services? Our second question focuses on three specific dimensions of life in these areas that we hypothesize may considerably influence energy access: migrant status (recent vs. long established); settlement status (formal vs. informal); and seasonality (dry vs. monsoon).

Our study fills three gaps. First, we explore the important question of energy access and energy poverty in an LMIC urban setting. The majority of studies addressing energy poverty focus on rural settings. Second, we focus specific attention on migrant and settlement status as hypothesized demographic determinants of energy access and energy poverty in rapidly growing neighborhoods of a future Southeast Asian mega-city. Lastly, Myanmar has had limited attention from the energy research community despite major energy transitions taking place in the country. The study aims to provide critical and timely knowledge on constraints to modern energy access for the urban poor, new migrants, and other marginalized groups in one of the fastest growing cities in Southeast Asia.

2. Methods

2.1. Study area

Yangon City is located in Yangon Region in lower Myanmar bordered on the south by the Gulf of Martaban. Yangon Region is divided into four districts: Northern, Eastern, Southern, and Western. The four study sites are located in the Northern District in Htantabin and Hlaingtharya Townships (Fig. 1). We selected this area for our study for two reasons. First, we believe Hlaingtharya is broadly representative of rapidly growing high-density suburbs around Myanmar's major cities. Second, Htantabin is an excellent example of a rural area that is likely to transition to urban in the coming decade. By selecting these adjacent townships we are able to characterize heterogeneity within urban sites, make distinctions in energy access between urban and urban adjacent rural areas, and consider the potential energy access futures of urban adjacent sites.

Htantabin (Site 1) is predominantly rural with an agriculture based economy. Htantabin's share of population in the agricultural sector (45%) is comparable to the national average (51.7%), suggesting it is broadly representative of rural areas with respect to livelihood strategies (Table 1). Yangon City is expected to rapidly expand further to the north and transform Htantabin into a satellite town with several industrial and infrastructure projects in the planning stages [45]. Hlaingtharya (Sites

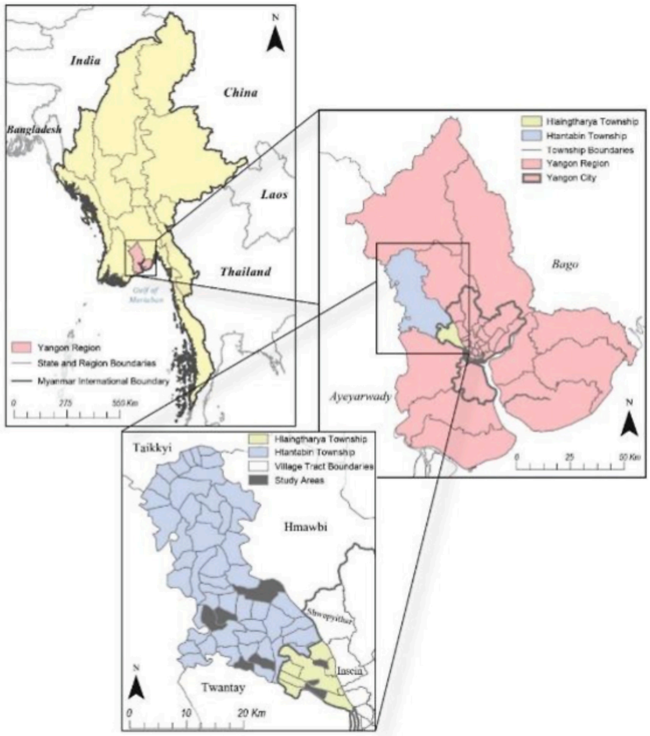

Fig. 1. Study area.

2/3/4), established in 1985 to provide a home for relocated inner city populations, and rural migrants [46], borders Htantabin to the south and is one of the oldest satellite townships in Yangon. Hlaingtharya is the most populous township in all of Yangon City [47]. The township has 12 industrial zones, the highest number in Yangon Region [48]. Industrial development in Yangon Region has attracted many rural migrants and national data on rural–urban migration shows the majority of migrants head towards North and East Yangon, which includes Hlaingtharya Township [49]. Notably, the garment and light industries situated in Hlaingtharya have attracted many female migrants to the township [49], which may explain why it has a higher share of female headed households than neighboring Htantabin (20.4% vs. 16.2%). Hlaingtharya Township was also a major destination for rural migrants from the Ayeyarwaddy Delta after Cyclone Nargis hit that region in May 2008 leading to widespread loss of human life, destruction of property, and economic loss in lower Myanmar [50].

The two townships, despite being immediately adjacent to each other, provide a contrast in both extent of urbanization and energy access. Hlaingtharya, considered mostly an urban town, falls under the administration of Yangon City Development Committee (YCDC), which provides municipal services to the urban population, including urban planning (zoning), solid waste management and sewage, water supply and sanitation [47]. Both townships fall under the jurisdiction of Yangon Electricity Supply Corporation (YESC), a government body responsible for electricity provision. Only 20% of Htantabin households compared to 76% of Hlaingtharya households have access to electricity for lighting. Energy access for cooking is also different with the majority of households in Htantabin (80%) using firewood as their primary cooking fuel, compared with Hlaingtharya where electricity (41%) and charcoal (50%) are the most commonly used cooking fuels. Energy access in Htantabin is expected to change quickly with grid extension and industrial development in the region [51].

2.2. Study design

We used a mixed method two-wave observational study design that compares energy access for households in four purposively selected study sites representing varying stages of urbanization. Our rural–urban designation is consistent with the 2014 Myanmar Census, which defines the rural population as those living in village tracts, and the urban population as those living in wards [52]. However, our rural site is adjacent to a major metropolitan area, meaning that it does not represent the average experience of village tracts throughout Myanmar. Sites 1 through 4 are broadly characterized along a rural to urban continuum from most rural (Site 1) to the most established urban development (Site 4) as follows: rural (Site 1/rural); high density informal settlement population (Site 2/ Yeokkan Ward); industrial zone/residential mix (Site 3/Shwelinban Ward); and established residential formal settlement (Site 4/Ward 7). Site 1 falls within Htantabin Township (outside the Yangon City limits) and the remaining sites 2–4 fall within the satellite town of Hlaingtharya Township (e.g., within Yangon City limits) (Fig. 1). Our intention in selecting these sites was to broadly represent the diversity of urban settings and socioeconomic conditions that currently exist in Yangon's satellite towns and in rural areas immediately adjacent to urban development that are poised for urbanization.

Table 1
Sociodemographic and household energy characteristics in Htantabin and Hlaingtharya Townships based on 2014 Census

Characteristics	Htantabin Township	Hlaingtharya Township
Population (persons)	145,792	687,867
Population density (person/km^2)	240	10,211
Urban population (%)	6.2	70.1
Urban wards	5	20
Village tracts	54	9
Mean household size (persons)	4.2	4.5
Female headed households (%)	16.2	20.4
Employment industries (% of households)		
Agriculture, forestry and fishing sectors	45	2
Manufacturing	16.2	29
Wholesale and retail trade, repair of motor vehicles and motorcycles	8.1	14
Construction	5.5	16
Transportation and storage	4.8	10
Accommodation and food service activities		12
Main source of energy for cooking (% of households)		
Electricity	12.7	41.3
Firewood	79.8	6.0
Charcoal	5.5	49.6
LPG	< 0.1	0.5
Main source of energy for lighting (% of households)		
Electricity	20.1	76.3
Kerosene	29.7	0.1
Battery	27.6	8.5
Candle	12.7	2.4
Generator (private)	5.3	12.1
Solar system/energy	4.2	0.2

Source: Department of Population, The 2014 Myanmar Population and Housing Census: Htantabin Township Report, Nay Pyi Taw, 2017. https://themimu.info/sites/themimu.info/files/documents/TspProfiles_Census_Htantabin_2014_ENG.pdf Department of Population, The 2014 Myanmar Population and Housing Census: Hlinethaya Township Report, Nay Pyi Taw, 2017. http://themimu.info/sites/themimu.info/files/documents/TspProfiles_Census_Hlinethaya_2014_ENG.pdf (note: Hlinethaya is an alternative spelling of Hlaingtharya)

2.3. Sampling and data collection

2.3.1. Quantitative survey sample

In Htantabin (Site 1), we obtained a map of village locations from the township office. We assigned numbers to the villages and used a random number generator to choose five villages for our study (Asugyi, Chaungnyiko, Kyahone, Kyeinpaik, and Payut). Prior to data collection, we conducted a census in the each of the five selected villages where the field team collected names of all households from village chiefs. After assigning a number to each household, we used the Excel random number generator to pick 30 households from each village for a total sample size of 150 rural households. Each village had approximately 150 to 200 households, suggesting that we have captured 15–20% of the total number of households in each village.

In Hlaingtharya (Sites 2/3/4), we purposely chose the three wards (Yeokkan, Shwelinban, and Ward 7) that represent different urbanization stages. We then, obtained copies of ward-level maps from the ward offices, gridded the maps, and numbered them. We randomly chose ten numbers, and the matching grids were selected as sampling sites. Similar to the rural site, we conducted a census exercise in the selected grids, which involved the field team members walking randomly selected streets to collect names of household heads until 60 to 80 households were collected. The teams conducting the census were accompanied by a community leader who provided household head names if nobody was home. From the list of 60–80 households, we randomly selected 15 households from each of the ten grids, resulting in 150 households sampled in each of Sites 2, 3 and 4, for a total sample of 450 urban households. In summary, the order of random sampling in the urban sites was at three levels: grid, street, and household. While our sample is not population representative, we feel that our sampling strategy allowed us to capture the range of households in the study area. We conducted two waves of data collection to capture potential seasonal variations in energy access with each wave of data collection taking approximately four weeks. Wave 1 was administered in the dry season, December 2018 through January 2019. Wave 2 survey was conducted from September to October 2019, representing the tail end of the monsoon season.

Of the 600 households surveyed in the first wave, 463 households (77%) remained for repeat sampling in the second wave. To address attrition in the monsoon season (wave 2), we implemented the following replacement strategy to maintain a 600 household sample. For each household lost to follow up in wave 2, we randomly chose a replacement household from the list of households collected during the study's census exercise in the same village/grid used for drawing our original sample. The 137 households lost to follow-up were replaced in wave 2 with a randomly selected new household from the same village/block to maintain the 600 household sample size per season. This resulted in 737 unique households (600 from wave 1 plus 137 replacements in wave 2) in the study sample. Comparison of socio-economic characteristics between those lost to follow-up with replacement households as well as those that remain in the study for both seasons (repeat households) are provided in Supplementary table (Table S1).

2.3.2. Qualitative survey sample

We conducted in-depth qualitative interviews with a subset of the urban households (N = 20) selected from among those we interviewed for the quantitative survey. We predetermined our sample sizes to ensure saturation in relevant subgroups (i.e., recent vs. long- established residents) [53] following previous literature that suggests that majority of new information is revealed in the first five to ten interviews, and that little new information is gained as the sample size approaches 20 interviews [54–58]. We restricted our interviews to the urban study area because we were primarily interested in the lived experiences of low-income urban households. All households interviewed were in Yeokkan Ward (Site 2), where the majority of informal settlers and low-income households reside.

Our initial objective was to conduct 20 in-depth qualitative interviews with female head of households equally divided between recent migrants and long-established residents. The purpose of the in-depth interview was to explore narratives of energy poverty and access for women in a Yangon satellite township. However, it became clear during the recruitment process that it was difficult to find 20 female-headed households due to their limited number in our study sample. We expanded our criteria to include households with male-headed households, thus allowing us to include a sub-analysis on gender. Out of the 20 household interviews, 13 were female-headed households, and of those, six were short-term residents and seven long-term residents. The remaining seven households were male-headed households, of which three were recent migrants and four long-term residents (Table S2).

2.3.3. Structured household surveys

We conducted structured household surveys in 600 households: 150 in Htantabin Township and 450 in Hlaingtharya Township distributed equally across the three urban sites. The household questionnaire included modules on: household demographics; assets; energy use (e.g., cooking, lighting, small-scale business), time use, expenditures, social capital, livelihood strategies, and self-reported air pollution related health outcomes (e.g., respiratory infection; eye irritation, etc.).

The survey was prepared in English and translated into Burmese by a professional third party translator. It was back translated into English by a researcher from the study team who is bilingual in English and Burmese, to check for consistency. We coded the data collection platform for the survey in Open Data Kit (ODK) software in both English and Burmese, and data captured by the field team during interviews using electronic tablets. Interviews took place in Burmese, a language widely spoken in Yangon, with the duration of the survey ranging from 45 min to 1.5 hour. Research partners from the Yangon University of Education and University of West Yangon facilitated permissions from local township offices and ward officials.

We recruited an experienced team for survey administration, including 15 enumerators and 3 field supervisors. The field supervisors were responsible for finding and recruiting survey respondents following the study criteria and ethics protocol, coordinating across the field teams, and managing local relations within the community. We trained the field team over a 5-day period. The training included familiarization with study's objectives, sampling plan, and survey questions, an overview of research ethics, practicing electronic data collection, mock interviews, and pilot testing in a nearby community in Yangon City. Data quality checks were performed by field supervisors daily before uploading to a secure data server hosted at the Carolina Population Center. After data were uploaded to the server, a researcher from the study team conducted a secondary data quality check.

2.3.4. Qualitative interviews

In our structured interviews with 20 urban households, we analyzed barriers as well as aspirations for use of clean cooking and lighting fuels and technologies in a high-density, low-income urban township in Yangon. We explored whether the barriers and opportunities differ across gender, migrant history, and informal status of household heads. The interviews aimed to shed light on how energy access affects urban households with female head of households compared to male head of households. We also explored how the experiences differ between recent migrants ($<$5 years of residence in Yangon City) versus long-established residents ($\geq$5 years of residence in Yangon City) to understand experiences of energy poverty and access for those migrating to an urban setting. We purposively selected our respondents to include those who were informal and formal residents, new migrants and long-established residents, and female and male-headed households, hypothesizing that their energy access situations might be quite different.

We conducted in-depth interviews with head of households above 18 years of age. The interviews took place 5–14 days after the quantitative survey was administered. We conducted all interviews in Burmese. We recorded interviews; participants had the option to opt out of having interviews audio recorded and still participate in the interview. A bilingual member of the field team transcribed and translated the interviews to English. Due to financial and logistical constraints, in-depth interviews were limited to wave 1 of the study.

2.4. Analysis

2.4.1. Quantitative survey data

We compared indicators of energy access between rural and an aggregation of urban sites, and across the three different urban sites. We generated descriptive statistics and comparisons between groups were performed using Wilcoxon rank-sum and Kruskal-Wallis tests. We undertook binary logistic (logit) multivariate regressions to investigate the sociodemographic and structural determinants of energy access. We conducted two types of analyses: 1) cross-sectional analyses of 600 households for each season (dry and monsoon); and 2) a panel analysis that included only households that were present for both seasons/waves of data collection (N = 463). The panel analysis used random effects model with random intercepts for households to examine seasonal differences in household energy access. For each of the analyses, we ran models with combined urban and rural samples, and analyzed urban and rural samples separately as predicators may be different between rural and urban areas.

We calculated odds ratios for the following outcomes: 1) access to national electricity grid (equation (1)); and 2) exclusive use of clean energy for cooking (electricity/gas) and lighting (electricity/solar) (equation (2)). We considered electricity, gas, and solar as "clean" because they do not contribute to in-home emissions at point of use.

National grid access was based on a binary response, which asked whether the household is connected to the grid. Fuels used for cooking and lighting were derived from questions that asked for percent share of fuels used in the past seven days. For example, a household that exclusively used electricity for cooking in the past seven days (100% clean fuel used) was categorized in the exclusive clean cooking fuel user group. The reference category included two types of households, those that are exclusive users of polluting fuels and those who are mix fuel users. Polluting fuels include wood, charcoal, diesel generator, candle, kerosene and garbage.

For the grid access analysis, we did not include data from households in the three rural villages that did not have any grid infrastructure at the time of our survey because we are interested in household-level determinants of grid access where grid infrastructure is available. For all other outcomes, we included all households regardless of presence of grid infrastructure. All regression models (Eq. 3) included covariates, such as age, gender, education, migration history, occupation of household head, settlement status, family size, floor and wall materials, social capital, and membership in community organizations. Several studies of drivers of urban and rural household energy transitions use socioeconomic indicators such as education and gender of household head, household size etc. as important predictors of household energy use [27,59–62].

$$y = \log(Pr(grid\ acces = 1)/1 - Pr(grid\ access = 1)) \tag{1}$$

$$y = \log(Pr(use clean fuel exclusively = 1)/1 - Pr(use clean fuel exclusively = 1)) \tag{2}$$

$$\begin{aligned} y = g(&\beta_0 + \beta_1 Informal + \beta_2 Location + \\ &\beta_3 Householdhead\ age + \beta_4 Householdhead\ gender + \beta_x X + ...) + \delta \end{aligned} \tag{3}$$

where y is the outcome of interest, β_0 is intercept, β_1 is informal status, β_2 are dummy variables for location (wards, villages), β_3, β_4, …, β_x are coefficients for control variables and δ is error term.

Given the lack of a formal definition of an "informal" status in Myanmar, we used selected criteria to assign informal status to households in our sample. Informal households were those who: 1) do not own the house where they live and do not pay house rent; and 2) do not own the land they are currently residing on nor pay land tax. We considered all rural households to have formal status. Social capital is an aggregate variable that indicates whether household members have relatives or acquaintances who worked in hospitals or clinics (i.e. as doctors, nurses, midwife, administrators); schools (teachers, administrators), and in government service. Community membership indicates participation in community groups, such as agricultural, microfinance, civic, and religious organizations.

All models included cluster-robust standard errors at the ward/village level to allow for intragroup correlation, as households within each ward or village are likely to be more similar than those from other wards/villages. We created dummy variables for each location (three urban wards - Yeokkan, Shwelinban, Ward 7; and five rural villages – Asugyi, Chaung-nyiko, Kyahone, Kyeinpaik, and Payut) as ward/village level controls. For the panel analysis, we explore seasonal variation in energy access by including a dummy variable for season. We checked for multicollinearity using the variance inflation factor (VIF); VIFs were below 3.5 in all models. We employed diagnostic tests to check for relative goodness of model fit using Bayesian Information Criterion (BIC), Akaike's Information Criterion (AIC) values. Our use of the term "significant" throughout the manuscript indicates statistical significance with $p < 0.05$. The quantitative analyses were conducted using STATA 15.1 SE [63].

2.4.2. Qualitative interview data

To analyze the qualitative interview data, we developed a codebook using deductive codes based on a review of the literature, and inductive codes based on emerging themes from the interviews. The codebook consists of main codes used to distinguish the different sections in the interview guide, and of sub-codes that emerged from the data. The codebook was developed using the qualitative analysis software program NVIVO 12 Plus, and was checked prior to analysis by the lead investigator. We assigned attributes to each interview file to classify them according to the gender of household head, settlement patterns, and cooking and lighting fuels.

2.5. Human Subject's review

All study participants gave their informed consent for inclusion before they participated in the study. We conducted the study following a protocol approved by the Institutional Review Board (IRB) of the University of North Carolina at Chapel Hill (UNC-Chapel Hill) (#18–2735).

3. Results

3.1. Grid access, energy assets and expenditure, quality of access

A little over one third (37%) of rural households have grid connection compared to 86% of urban households (Table 2). However, across the three urban wards, grid connection is highly variable, ranging from 58% in Yeokkan (Site 2) to 99% of households in Ward 7 (Site 4). Batteries are the secondary major source of electricity after grid connections for 30% of rural households, and 23% of urban households. Battery types ranged from car batteries that can be charged by solar panels (primarily seen in rural areas) to smaller batteries that can light a bulb for four hours. In Yeokkan (Site 2) where the grid access rate is the lowest, 46% of households rely on batteries, the highest among the urban wards. Wave 2 monsoon season had similar patterns in energy access across rural–urban and inter-urban comparisons. Grid access rates remain similar between the two seasons; however, we observe seasonal differences in batteries used as an electricity source. The proportion of urban households relying on batteries declined by half from 23% to 10% in the dry and monsoon seasons, respectively. The reduction is observed across all three urban wards; the highest decline is in Ward 7 (Site 4) where the proportion of households using batteries declined from 13% to just 2% in monsoon.

Ownership of electric cooking devices across the different sites followed the same pattern observed for grid electricity access. Roughly a third of rural households and about 80% of urban households owned

Table 2
Descriptive statistics on energy access, mean (standard deviation in parentheses).

	WAVE 1 (DRY SEASON)							WAVE 2 (MONSOON SEASON)						
	Rural (Site 1)	Urban^ (Site 2/3/4)	Ward Yeokkan (Site 2)	SLB(Site 3)	Ward 7#(Site 4)	All	Min-Max	Rural (Site 1)	Urban^ (Site 2/3/4)	Ward Yeokkan (Site 2)	SLB(Site 3)	Ward 7#(Site 4)	All	Min-Max
HOME ELECTRICITY SOURCE														
National grid (0/1)	0.360	0.844***	0.575	0.961	0.987***	0.723	0–1	0.373	0.856***	0.596	0.993	0.980***	0.735	0–1
Mini-grid (0/1)	0.007	0.020	0.048	0.013	0.000***	0.017	0–1	0.000	0.036**	0.099	0.000	0.007***	0.027	0–1
Diesel generator (0/1)	0.020	0.031	0.075	0.000	0.020***	0.028	0–1	0.000	0.033**	0.066	0.007	0.027**	0.025	0–1
Batteries (0/1)	0.300	0.229*	0.459	0.105	0.132***	0.247	0–1	0.267	0.104***	0.265	0.027	0.020***	0.145	0–1
ENERGY RELATED ASSETS														
Electric curry pot (0/1)	0.273	0.773***	0.493	0.948	0.868***	0.648	0–1	0.287	0.780***	0.530	0.946	0.867***	0.657	0–1
Electric rice cooker (0/1)	0.340	0.809***	0.527	0.961	0.927***	0.692	0–1	0.347	0.813***	0.563	0.960	0.920***	0.697	0–1
Electric coil stove (0/1)	0.013	0.020	0.034	0.013	0.013	0.018	0–1	0.027	0.029	0.020	0.034	0.033	0.028	0–1
Induction stove (0/1)	0.113	0.031***	0.027	0.039	0.026	0.052	0–1	0.080	0.051	0.026	0.074	0.053	0.058	0–1
Gas stove (0/1)	0.020	0.091***	0.062	0.052	0.159***	0.073	0–1	0.053	0.149***	0.086	0.128	0.233***	0.125	0–1
Improved cookstove (0/1)	0.327	0.504***	0.603	0.431	0.483***	0.460	0–1	0.227	0.502***	0.596	0.436	0.473***	0.433	0–1
Solar panel (0/1)	0.440	0.020***	0.062	0.000	0.000***	0.125	0–1	0.500	0.018***	0.046	0.007	0.000***	0.138	0–1
EXPENDITURE														
Energy expenditure per capita (MMK/person)	2,306 (5,079)	3,792*** (4,781)	5,171 (5,887)	2,983 (3,499)	3,278*** (4,443)	3,420 (4,896)	0-42,857	1,939 (3,677)	4,530*** (5,539)	5,256 (4,979)	4,593 (7,844)	3,737* (2,281)	3,882 (5,256)	0-85,000
Total expenditure per capita (MMK/person)	85,133 (56,589)	108,282*** (58,541)	109,598 (72,666)	102,877 (48,876)	112,486 (51,807)	102,495 (58,873)	4,500–556,836	71,986 (50,131)	104,225*** (53,993)	105,432 (59,316)	100,585 (50,020)	106,627 (52,318)	96,165 (54,823)	7,925–367,456
Share of energy expenses of household expenditures (%)	3.06 (6.40)	3.81*(4.23)	5.15 (5.28)	3.36 (3.69)	2.98*** (3.17)	3.62 (4.87)	0.00–54.55	2.94 (5.44)	4.85*** (4.91)	5.58 (4.77)	4.82 (6.16)	4.14 **(3.30)	4.37 (5.11)	0.00–54.60
N	150	450	150	150	150	600		150	450	151	149	150	600	
QUALITY OF ACCESS IN PAST WEEK IN SUBSET HOMES WITH GRID														
Electricity available in a day (hours)	23.09 (0.73)	21.29*** (2.94)	22.27 (1.67)	20.60 (3.23)	21.42*** (3.03)	21.52 (2.82)	5–24	22.42 (1.40)	21.37*** (2.53)	21.15 (2.77)	21.40 (2.59)	21.48 (2.33)	21.51 (2.44)	5–24
Electricity available in evening (hours)	3.54 (1.07)	3.19**(0.91)	3.36 (0.94)	3.07 (0.98)	3.22* (0.80)	3.24 (0.94)	0–4	3.63 (0.46)	3.00*** (1.01)	2.98 (1.00)	2.90 (1.12)	3.10 (0.88)	3.08 (0.98)	0–4
Voltage fluctuations (0/1)	0.06	0.25***	0.26	0.18	0.31**	0.23	0–1	0.23	0.38**	0.32	0.32	0.48**	0.36	0–1
Blackouts (number)	2.44 (1.57)	5.07*** (0.91)	6.38 (0.94)	4.92 (4.40)	4.49** (4.69)	4.75 (5.14)	0–28	4.04 (3.39)	4.98*(3.96)	5.50 (3.98)	5.00 (3.74)	4.63 (4.16)	4.86 (3.90)	0–30
Duration of blackouts (hours)	1.92 (4.20)	6.60*** (12.04)	7.68 (16.08)	7.49 (12.03)	5.10 (8.91)	6.01 (11.46)	0–98	4.04 (5.31)	5.13(5.37)	5.18 (4.80)	5.22 (5.01)	5.02 (6.05)	4.99 (5.37)	0–35
N	54	380	84	147	149	434	–	56	385	90	148	147	441	–

^represents statistically significant differences between rural and urban households in each season; #represents statistically significant differences across three groups/urban wards in each season. Statistical significance indicated by *$p < 0.10$; **$p < 0.05$; ***$p < 0.01$. SLB = Shwelinban; MMK = Myanmar Kyat.

either an electric curry pot or a rice cooker. LPG stove ownership ranged from 5% in rural to 15% in urban households (Table 2). However, their usage appeared to be limited, and may be used only as a secondary or backup fuel as indicated by share of cooking fuel types. Share of LPG used for cooking in the past seven days ranged about 2–2.5% for both urban and rural households (Fig. 2; Table S3). A substantial number of urban households also owned improved biomass cookstoves, ranging from 43% of households in Shwelinban (Site 3) to 60% in Yeokkan (Site 2). The most frequently observed improved cookstoves in the study area were domestically produced enclosed mud stoves typically used with charcoal, and sometimes wood. Solar panel ownership was significantly higher in rural (44%) compared to urban (2%) households. In the rural area, solar panel ownership was as high as 83% in a village with no grid access (Table S5). In the urban areas, we observed solar ownership only in Yeokkan (Site 2). Seasonal comparison revealed an average increase in proportion of rural households who own solar panel from 44% to 50%, whereas it stayed the same for urban households.

Energy expenditures per capita for the 30 days prior to the interview were significantly lower for rural than urban households. Mean energy expenditures for rural and urban households were 2,306 kyats ($1.45)/person/month, and 3,792 kyats ($2.39)/person/month, respectively. Rural households spent 3.1% of total expenditures on energy, which was not statistically different from 3.8% for urban households ($p > 0.05$). Yeokkan (Site 2) had the highest per capita energy expenditures (5,171 kyats ($3.26)/person/month) and the highest share of total expenditures on energy (5.2%). In wave 2 (monsoon season), per capita energy costs reduced by 16% for rural households but increased by 19% for urban households. The share of expenditures on energy was also higher in wave 2 for urban households (3.8% in wave 1 vs. 4.85% in wave 2). The increase was particularly apparent in wealthier wards (SLB (Site 3) and Ward 7 (Site 4)). Prior to our second round of data collection, i.e. wave 2, YESC increased electricity tariffs slightly. The effect of the increase was likely smaller in Yeokkan, as 40% of the study population in the ward did not have grid access.

Among households with grid connection, rural households have a significantly better quality of electricity compared to urban households. For example, rural households have significantly more hours of electricity available in a day (23 vs. 21 h/day), and at night (3.5 vs. 3.2 h/night). In addition, a lower proportion of rural households experience voltage fluctuations compared to urban households (6% vs. 25%), lower incidence of blackouts (2% vs. 5%), and shorter blackout duration (1.9 vs. 6.6 h/blackout). Across the urban wards, Shwelinban (Site 3) reports the lowest hours of electricity typically available in a day (20.6 h) compared to 21.4 h in Ward 7 (Site 4), and 22.3 h in Yeokkan (Site 2). However, the number and duration of blackouts are highest in Yeokkan.

Seasonal differences are notable for quality of electricity access, especially in the rural area. A higher proportion of rural households experienced voltage fluctuations in the monsoon (23%) compared to the dry season (6%). Rural households also reported a higher frequency and longer duration of blackouts in the monsoon compared to the dry season. A higher proportion of urban households reported voltage fluctuations in the monsoon compared to the dry season, however, duration of blackouts were shorter in the monsoon (5.1 h) compared to the dry season (6.6 h).

Wood and electricity were the dominant cooking fuels for rural households, providing 67% and 32% share of total fuels used, respectively (Fig. 2, Table S3). In the urban wards, electricity was the major cooking fuel, constituting 90% share of cooking fuels used in Shwelinban (Site 3) and 85% in Ward 7 (Site 4). In Yeokkan (Site 2), electricity was less dominant, providing only 52% of cooking fuel share, with the remaining supplemented by charcoal (37%) and wood (9%). Use of liquefied petroleum gas (LPG) for cooking is limited in the study sites making up<4% of the share of cooking across all sites. Slight seasonal differences were observed including increases in share of charcoal (0.8% to 3.5%) and LPG (0.3% to 1.8%), and a decrease in share of electricity (32% to 29%) between the dry and monsoon seasons for rural households (Table S3). Urban cooking fuel shares moved in the opposite direction with reductions in share of charcoal and wood in monsoon, and an increase in electricity share, particularly in SLB (Site 3) and Ward 7 (Site 4), which have more industrial development and smaller informal settlement population, in the dry season.

Lighting for rural households is dominated by solar (39%), electricity (33%), and battery operated devices (14%) (Fig. 3; Table S3). In urban areas, electricity provided the majority share of lighting energy (51% in Yeokkan (Site 2); and over 80% in Shwelinban (Site 3) and Ward 7 (Site 4)). Battery operated devices constituted roughly a third of the share of lighting fuels in Yeokkan (Site 2). In monsoon, rural households had a slight seasonal increase in share of candles (8% vs. 11%) and solar (39% vs. 43%) used for lighting. At the same time, there was a slight decrease in share of kerosene and battery operated devices used. For urban households, electricity as a share of lighting fuel slightly increased from 74% in dry season to 77% in monsoon, and battery operated devices reduced from 16% to 12% over the same period.

We use the panel/repeated household sample (N = 463) to compare our main indicators of energy access, grid access rate, exclusive use of clean fuels for cooking (electricity/gas), and exclusive us of clean fuels for lighting (electricity/solar), across the four study sites (Sites 1/2/3/4) and two seasons (dry and monsoon) (Fig. 4). The proportion of households using clean fuels exclusively for cooking and lighting is lower than grid access across all four sites and seasons. An exception is for rural lighting where a larger proportion of rural households are exclusive clean lighting fuel users (44%) than those connected to the grid (36%).

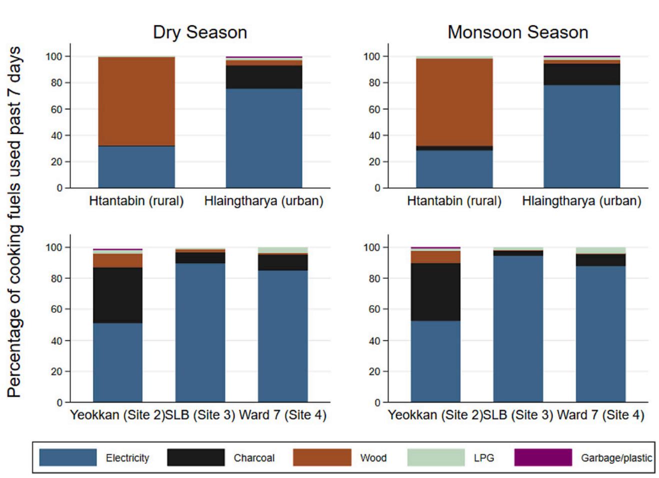

Fig. 2. Share of cooking fuels by location and seasons.

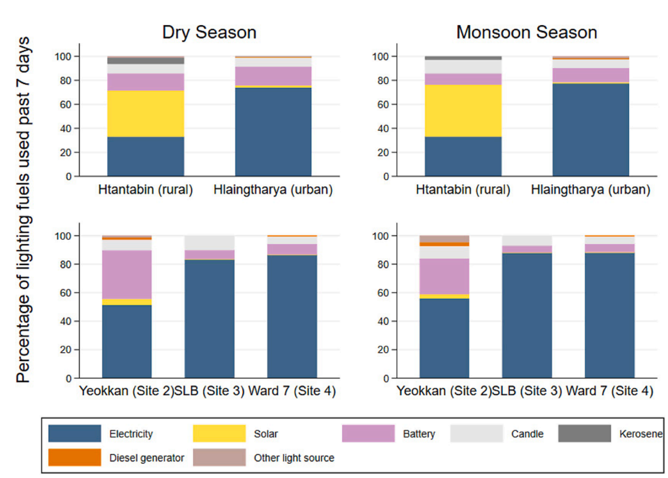

Fig. 3. Share of lighting fuel by location and season.

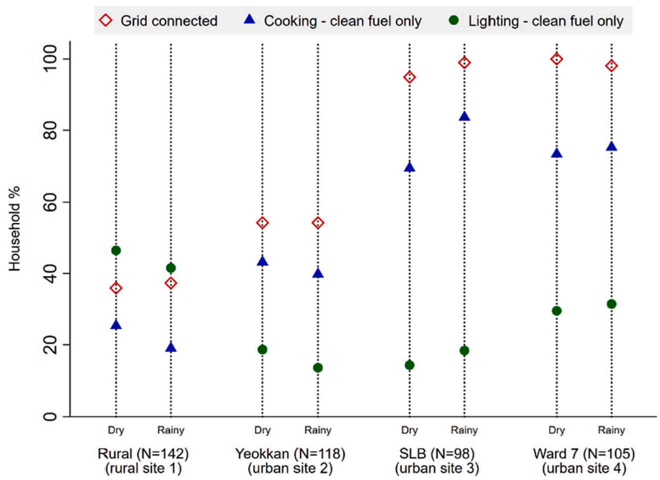

Fig. 4. Energy access indicators across study sites and season (N = 463).

Further, a greater share of rural households are clean lighting fuel users compared to the urban households (44% vs. 21%). Despite significant variation in urban grid access rates (54%-99%), the proportion of households who are exclusive clean lighting fuel user are surprisingly low across the three urban wards, ranging between16% in Yeokkan (Site 2) and Shwelinban (Site 3) to 30% in Ward 7 (Site 4).

We observe seasonal differences in the proportion of households using clean cooking and lighting fuels exclusively. A lower proportion of households in rural (Site 1) and Yeokkan (Site 2) households used clean fuels exclusively for cooking and lighting in monsoon compared to dry season. Conversely, a higher proportion of Shwelinban (Site 3) households used clean cooking and lighting fuels exclusively in the monsoon compared to the dry season.

3.2. Sociodemographic characteristics

We present data for sociodemographic characteristics from wave 1 of the data collection in Table 3, as we do not expect most of these variables to change over the course of half a year (for descriptive statistics for monsoon season see Table S4). Rural households have a significantly larger family size compared to urban households with 4.2 vs. 3.6 persons, and older age of household head with 50.8 vs 42.2 years (Table 3). The 2014 township census ([51,64], Table 1), report a similar average rural household size of 4.2 persons in Htantabin. We note that Hlaingtharya Township census indicated a household size of 4.5 persons per household compared to our urban study sample of 3.6 persons per household. The proportion of female-headed households is slightly lower in rural areas but not statistically significantly different from urban areas (16% vs. 22%). Heads of households in rural areas have fewer years of education; for example, only 19% of rural household heads have secondary and above education whereas 54% of urban household heads have secondary and above education.

Across the three urban wards, the age of household head is significantly different among the three sites; Yeokkan (Site 2) has the youngest average age of household head (41 years), compared to 45 years in Ward 7 (Site 4). There are no other significant differences in family size, education or gender between the three urban sites.

A larger proportion of urban households have a recent history of mobility reflected by duration of time lived in the current house and in

Table 3
Descriptive statistics for socioeconomic characteristics of households, mean (standard deviation in parentheses).

	WAVE 1 (DRY SEASON) Rural(Site 1)	Urban^(Site 2/3/4)	Ward Yeokkan(Site 2)	SLB(Site 3)	Ward 7(Site 4)	All	Min-Max
Family size (person)	4.19(1.61)	3.62***(1.59)	3.51(1.645)	3.65(1.47)	3.69(1.646)	3.76(1.61)	1–11
Age of household head (years)	50.81(13.12)	42.24***(14.88)	40.76(13.98)	41.41(15.08)	44.51*(15.33)	44.38(14.92)	18–90
Female headed household (0/1)	0.160	0.222	0.219	0.229	0.219	0.207	0–1
Head education							
None (0/1)	0.167	0.080***	0.116	0.052	0.073	0.102	0–1
Primary (0/1)	0.647	0.373***	0.390	0.386	0.344	0.442	0–1
Lower secondary (0/1)	0.107	0.280***	0.274	0.301	0.265	0.237	0–1
Upper secondary & above (0/1)	0.080	0.267***	0.219	0.261	0.318	0.220	0–1
Head lived in current house							
<1 year (0/1)	0.007	0.293***	0.219	0.418	0.238***	0.222	0–1
1–5 years (0/1)	0.107	0.300***	0.329	0.346	0.225**	0.252	0–1
>5 years (0/1)	0.887	0.407***	0.452	0.235	0.536***	0.527	0–1
Head lived in Yangon Region							
<5 years (0/1)	0.007	0.316***	0.267	0.451	0.225***	0.238	0–1
5–10 years (0/1)	0.047	0.171***	0.185	0.163	0.166	0.140	0–1
>10 years (0/1)	0.947	0.513***	0.548	0.386	0.609***	0.622	0–1
Occupancy type							
Owner occupied (0/1)	0.987	0.313***	0.425	0.196	0.325***	0.482	0–1
Tenancy (rent paid) (0/1)	0.007	0.642***	0.479	0.765	0.675***	0.483	0–1
Tenancy (no rent paid) (0/1)	0.007	0.044**	0.096	0.039	0.000***	0.035	0–1
Informal (0/1)	0.000	0.222***	0.438	0.176	0.060***	0.167	0–1
Finished wall (0/1)	0.427	0.593***	0.411	0.739	0.623***	0.552	0–1
Finished floor (0/1)	0.147	0.538***	0.397	0.673	0.536***	0.440	0–1
Bank account at a formal institution (0/1)	0.147	0.236**	0.158	0.196	0.351***	0.213	0–1
Neighborhood/ Social environment							
Factories within 5 km of household (number)	0.03(0.16)	1.36***(1.42)	2.27(1.40)	1.03(1.22)	0.81***(1.17)	1.03(1.36)	0–7
Social capital score	1.11(1.12)	1.20(1.10)	1.01(1.09)	1.22(1.10)	1.36**(1.10)	1.18(1.11)	0–3
Membership in community organization score	1.38(1.34)	0.41***(0.70)	0.44(0.67)	0.44(0.76)	0.34(0.64)	0.65(1.00)	0–5
N	150	450	150	150	150	600	

^Represents statistically significant differences between rural and urban households; #represents statistically significant differences across three groups/urban wards. Statistical significance indicated by *p < 0.10; **p < 0.05; ***p < 0.01.
SLB = Shwelinban; "Finished wall" includes cement, stone with lime/cement, bricks, cement blocks, covered adobe, wood planks/shingles, and zinc. "Finished floor" includes parquet/polished wood, vinyl/asphalt strips, ceramic tiles, and cement. Social capital is an aggregate of binary values on whether household has family/ acquaintances in health care (doctors, nurses, midwife), education (teachers, school administrators), and government sectors. See Supplemental Section, Table S3 for wave 2 socioeconomic characteristics.

Yangon Region compared with rural households who were much more static. For example, 89% of rural households have been living in their current house for over 5 years, whereas this is the case for only 41% of urban households. Similarly, 95% of rural households report living in Yangon for over 10 years, whereas, only half (51%) of urban households report the same. Within the urban wards, Shwelinban (Site 3) has the largest proportion (42%) of households who have lived in their current house for less than one year compared to Yeokkan (Site 2) and Ward 7 (Site 4) at 22% and 24%, respectively. This is not surprising because Shwelinban (Site 3) has a relatively larger population of migrant factory workers who live in dormitory style apartments. They are likely to be more mobile depending on availability of factory jobs compared to residents from Yeokkan (Site 2) and Ward 7 (Site 4), which have a greater proportion of informal households (Site 2) and formal/long-term residents (Site 4), respectively. Similarly, for duration of time lived in Yangon, Shwelinban (Site 3) has the largest share (45%) of households who are recent migrants (lived in Yangon for<5 years) compared to 27% and 23% of households in Yeokkan (Site 2) and Ward 7 (Site 4), respectively. Shwelinban (Site 3) is home to a large Shwelinban Industry Zone with over 300 factories and reflects the rapid industrial development in the past five years.

Almost all rural households (99%) live in houses that they own (owner occupied) compared to just a third of urban households. The majority (64%) of urban households rented their homes. Across the

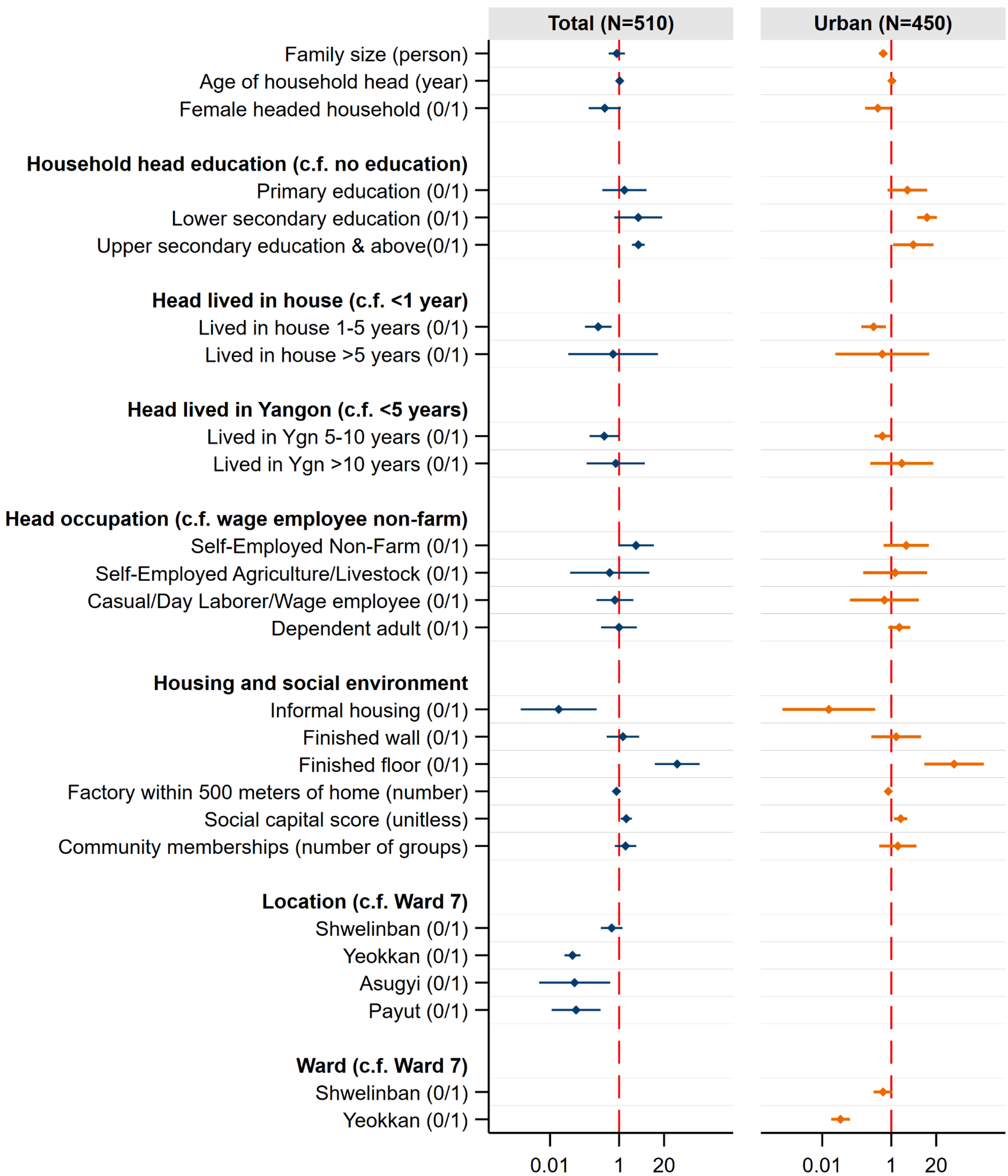

Fig. 5. Odds of grid electricity access (dry season). Note. Analysis with rural sample not shown due to small sample size (N = 66 rural households) after removing three villages that did not have grid infrastructure.

urban wards, Shwelinban (Site 3) had the highest proportion (77%) of households renting, as expected given that Shwelinban ward had a large population of migrant factory workers who typically rent apartments. About 10% of households in Yeokkan (Site 2) reported living in a house where they do not pay rent nor own the house, and this represents the highest proportion across all urban wards.

Yeokkan (Site 2) had the highest proportion of informal households at 44%, compared to 18% in Shwelinban (Site 3) and 6% in Ward 7 (Site 4). Indicators of wealth show that Yeokkan (Site 2) households are poorer compared to the other two urban wards; Yeokkan has the lowest proportion of households living in a house with a finished wall (41%) or floor (40%). In Yeokkan, bank account ownership is similar to what we observed in rural areas (~16%). In general, asset ownership of appliances used for cooling (e.g., refrigerator, fan, air conditioner) was lower in rural areas (when compared with urban), and in Yeokkan relative to SLB or Ward7. Television and radio ownership was consistent across all sites. For the rural sample, we considered asset ownership by grid connection status and found that refrigerator and electric van ownership was highly correlated with grid connection, whereas solar panel ownership was observed only in rural locations with no grid connection (Figure S1).

3.3. Predictors of grid connection

We assessed structural and social determinants of grid access using cross-sectional datasets for both seasons (Fig. 5; Tables S6a-S6b). We analysed the total and urban samples for grid access and did not run a rural model due to small sample size after removing villages that did not have grid infrastructure. Older age of household head was associated with 5% and 10% increased odds of having a grid connection in dry and monsoon seasons, respectively. Higher education was significantly associated with grid connection; the odds ratio ranged from 7.73 (95% confidence interval (CI): 4.22-14.16) to 10.85 (95% CI: 5.61-20.97) for lower secondary education, and 4.34 (95% CI:1.12-16.76) to 19.61 (95% CI:6.70-57.39) for upper secondary & above education compared to households with no education. Other determinants significantly associated with higher odds of grid connection are finished floor, higher social capital, and community memberships. In the sample of households surveyed in monsoon season, residents who have lived in Yangon longer than five or more years are five times more likely to have grid connection compared to those who have less than five-year residency. However, in the dry season, the odds were significantly lower for those that have lived in Yangon 5–10 years. Other determinants associated with statistically significant reduced odds of grid connection are family size; longer duration of stay in the house (significant for those in the 1–5 year category); occupation of household head (significant for the self-employed in farm and non-farm); informal status; and specific locations, namely (Yeokkan (Site 2) and rural (Site 1)). Female-headed household was associated with reduced odds of grid connection, which was significant in the dry season (0.41; 95% CI: 0.17-0.95).

3.3.1. Barriers to grid connection – qualitative interviews

Among urban households without access to electricity, the most commonly reported barriers to grid connection are informal residential status, lack of initiative to apply for electricity connection, and cost. Responses are similar for both female and male-headed households. All interviewed households who did not have access to grid electricity indicated wanting access, but were unable to obtain it due to their status as informal settlers or "squatters". The government does not grant squatters access to electricity because they lack land ownership and visitor's registration, which are stay permits required to apply for electricity. Lack of registration papers puts them under threat of eviction and sudden relocation. According to one respondent, only those who live in hostels (often factory workers) can obtain visitor registration cards.

Interview #16, male-headed household, female respondent, uses battery lighting:

"People from this area will not dare to expect that much because if we are ordered to move, we have to detach our houses and leave… And this administrator does not even give us visitor registration [stay permit] so who will let us to apply for the electricity? If we get up and apply who will accept that? Therefore, we end up with 100 kyat ($0.07)/day battery because we have no possessions… Now he does not give us visitor registration, so we dare not to expect electricity."

Respondents indicated that ward administrators are reluctant to help squatters. When discussing their informal status and inability to access electricity, two long-term migrants stated how this was a form of oppression and discrimination that minorities face. Squatters face threats of eviction and relocation by either landowners or the government.

Interview #6, female-headed household, female respondent, uses battery lighting:

"*We are discriminated against. People from the wards do not want to talk to us because we are squatters.*"

Two households interviewed were currently dealing with relocation issues. These households mentioned receiving a slip of paper from the government, meaning that they would have to leave their current location and move to a government-approved site. Some households responded that they have never tried applying for electricity because they have never heard of anyone applying in the area, thus, they never took the initiative to do it themselves. However, they believe that if people in the neighborhood collectively applied for electricity, or if someone takes the lead to apply, then it could be possible for them to access the grid. Some have given up any attempt to apply for grid connection, as they know the government will not approve given their informal status. Only two of the twenty respondents interviewed indicated that they had a financial barrier to accessing electricity. Two households indicated that even if they had an electricity source nearby, they said that would not be able to afford it.

3.4. Predictors of clean cooking fuel use

The odds of being an exclusive clean cooking fuel user (electricity/gas) was compared to a reference category which consisted of exclusive biomass fuel users and mixed fuel users (e.g., use both biomass and clean fuels) (Fig. 6; Table S7a-S7b). In the urban model, predictors significantly associated with reduced odds of being an exclusive clean fuel user were family size; lived in Yangon 5–10 or > 10 years (monsoon season);

household head whose occupation is a casual/day laborer/wage employee (dry season); and informal housing (dry season). Predictors associated with increased odds of exclusive clean fuel use were higher education; finished wall and floor (monsoon sample), and presence of factory within 500 m of household (dry season). We do not run a regression for the rural area because three villages had no exclusive clean cooking fuel users.

In the panel analysis, we found an effect of seasonality among rural households with significantly reduced odds (0.33; 95% CI: 0.28-0.38) for exclusive use of clean cooking fuel in the monsoon (Table S10). This may be due to increased frequency and duration of blackouts in monsoon in rural areas forcing households to resort to biomass fuels, particularly charcoal. Fig. 2 and Table S3 showed rural charcoal usage increased from 0.8% to 3.5%, and wood declined slightly from 67% to 66%. The limited availability of dry wood may also be the reason for higher usage of charcoal in monsoon compared to the dry season.

Urban households moved in the opposite direction with increased odds of being an exclusive clean cooking fuel user in the monsoon but the results were not statistically significant. Share of electricity used for urban cooking and lighting increased in monsoon compared to dry season (Table S3). We attribute this to higher water reserve from monsoon rains at the hydropower plants that produce electricity for Yangon City.

3.4.1. Barriers to clean cooking energy

The majority of households interviewed for our qualitative analysis use biomass fuels (wood/charcoal) (N = 16), and the remaining exclusively use electricity (N = 4) for cooking. The three most common barriers to using clean cooking energy, regardless of gender of household head, are cost, safety and inexperience. Some respondents indicated that electricity and gas are expensive or unaffordable, costing more than charcoal. Respondents express concern about both fixed and recurring costs, for example, fees to connect to an electrical grid and cost of a small gas canister.

Interview #16, male-headed household, female respondent, charcoal and wood user:

"*I can't afford it. Gas also need to be filled and it cost 500 kyats a bottle. It is okay to fill it up when I have money but what if I do not have money. It is expensive. Some who I know have gas at home. I cannot do that. I have to cook rice in the morning it is five cans, in the evening five cans. Gas bottle is tiny and will not sustain the pot of rice.*"

Interview #5, female-headed household, female respondent, charcoal user:

"I don't know how to cook with gas. Even if I can cook with it, a bottle of gas cost 500 kyats. There are some people who use gas around here but not everyone can afford…"

The remarks of our study respondents suggest that they are most familiar with very small gas cylinders. Though larger gas cylinders are available in Yangon, their cost and the need to transport them are likely prohibitive for low-income households. None of the respondents mentioned the additional fixed cost of purchasing a gas stove. This may be because many of our respondents have never cooked with a gas stove, making them unaware of the need for a specific stove and the associated startup costs. Safety is another common barrier to using adoption of gas for cooking. Many households believe that using gas is dangerous due to the potential for gas cylinder explosion. Lack of familiarity and inexperience using gas and electricity for cooking contributes to perceptions that modern fuels are difficult and dangerous to use. This perception was dominant among wood and charcoal users, as well as in both male- and female-headed households.

Interview #14, male-headed household, female respondent, wood user:

"*I am afraid to use it [gas]. I am afraid that it will suddenly explode while I am cooking.*"

Interview #4, female-headed household, female respondent, charcoal user:

"*R: I don't want to cook with gas.*

I: Why not?

R: I am afraid of it.

I: You are afraid of its danger, explosion.

R: Yes, yes."

Interview #9, female-headed household, female respondent, charcoal user:

"I don't know how to use [gas]. I dare not use. Because the houses are close to each other. In case of fire, it will be all gone. Therefore, it is good to use what we usually use. I dare not make changes in my cooking. I know that it is cheaper and less time consuming but I am afraid of the danger."

Interview #17, male-headed household, charcoal user:

"*I will choose charcoal stove because I am afraid of gas and electricity. I dare not use them. I have never used them before, so I am afraid to use.*"

Households stated reduced cooking time, convenience, and safety, as perceived benefits of using electricity and gas for cooking regardless of household head gender. Electric or gas stoves can reduce cooking time because stable heat is produced quickly, typically with a push of a switch/button, in contrast to charcoal and firewood, which requires people to start a fire and stand by to adjust the flame's intensity. Respondents also expressed that modern cooking fuels are more convenient. During the rainy season, many households report difficulties starting a fire with traditional fuels due to wood or charcoal fuels being wet or damp.

Respondents also indicated that modern cooking fuels allow people to multitask while cooking. For instance, when cooking rice with electricity, many households report that they could simply turn on the rice cooker and attend to other work while they let it cook on its own. This is difficult for households that use charcoal and wood, as they need to monitor the flame to adjust its heat (e.g. by adding more wood).

Interview #15, male-headed household, female respondent, wood user:

"*R: We want to use electricity because we can just use it and no need to watch it. We need not to take care rice cooker. We just need to let it cook.*

I: What difference does it have compared to others?

R: Others need to sit down and watch/take care."

Interview #1, female-headed household, electricity user:

"*Work is done faster by using electricity. And I can do other work while cooking rice.*"

Interview #16, male-headed household, female respondent, wood and charcoal user:

"I can just turn on the rice cooker and do other things whether washing clothes or cutting vegetables, washing fish and cutting fish. Cooking with charcoal, I have to watch it the whole time whether it will overflow... With this rice cooker it cooks automatically."

Another benefit of modern cooking fuel is that it can be used at any time. Some women noted that households using solid fuels have to limit their cooking activities to designated times (e.g., 4am – 10am and 4 pm – 10 pm). This is a rule enforced by ward administrators in an effort to allow concentration of limited resources to fight potential fire outbreaks to specific time windows during the day. Historically, major fire outbreaks have been reported in Yangon's squatter neighborhoods with major loss of property [40]. Use of biomass and kerosene combined with highly flammable house construction materials (e.g., thatch and wood) in high density settings mean that fires can spread easily [65]. Households caught cooking outside of designated hours are fined 5,000 kyats (US$ 3.33) by the fire brigade. People can apply for a fire certificate if they wish to use traditional fuels outside of designated hours, but those are typically granted for commercial purposes (e.g., shops) and are costly for most residents.

Interview #15, male-headed household, female respondent, wood user:

"It [charcoal] needs to be watched because of the worry for well heated charcoal to fall down."

Only female respondents mentioned cleanliness as a perceived benefit. Electric and gas stoves prevent pots from turning black, which makes it easier to wash as less scrubbing is required.

Interview #7, female-headed household, electricity user:

"*I: What is the difference between the use of electricity and charcoal?*

R: Using electricity is faster and using charcoal is slower.

I: What about cleanliness?

R: Using electricity is good for cleanliness and better. Using charcoal has to deal with ash, black pots, etc., and a lot of work to use it."

Moreover, fuelwood users point out that smoke produced from burning wood has negative health effects, especially for those with medical conditions making it necessary to constantly fan the smoke away. Finally, female respondents perceive that modern cooking fuels costs less than charcoal.

Interview #4, female-headed household, female respondent, charcoal user:

I: You have cooked with electricity in your sister's house. What do you think is the difference?

R: Charcoal costs more, I think.

I: What about electricity?

R: It doesn't cost much."

3.5. Predictors of clean lighting fuel use

The odds of being an exclusive clean lighting fuel user (electricity/solar) is compared to a reference category consisting of households that used basic/polluting fuels (candle/kerosene/diesel generator) and mixed fuels (use both polluting and clean fuels) (Fig. 7; Tables S8a-S8b).

In the urban sample, family size and households that lived in Yangon 5–10 years, and Shwelinban (Site 3) were significantly associated with lower odds of being an exclusive clean lighting fuel user in the dry season. In the monsoon season sample, significant predictors associated with lower odds of clean lighting fuel use were household head occupation as causal/day laborer and dependent adult, social capital and locations (Yeokkan (Site 2) and Shwelinban (Site 3)).

In the rural sample, family size, higher education, lived in house 1–5 years, and dependent adult, as household head was significantly associated with increased odds of exclusive clean lighting fuel use. Interestingly, in the total sample where both urban and rural households were combined in the analysis, rural households had statistically significantly higher odds of being an exclusive clean lighting fuel use compared to Ward 7 (Site 4) in the dry season. In the monsoon season sample, the three villages with no grid were the only ones with significantly increased odds of exclusive clean lighting fuel use. For example, households in Kyahone village, which does not have a grid, was 4.5 and 6.5 times more likely to be an exclusive clean lighting fuel user compared to Ward 7 (Site 4) in dry and monsoon season, respectively. Whereas, households in Asugyi, which has a grid, was 3.5 times more likely to be an exclusive clean lighting fuel user in the dry season but in the monsoon, odds were significantly reduced to 0.73 (95% CI: 0.58-0.92) compared to the reference location, Ward 7.

4. Discussion

We examine energy access in rapidly urbanizing Yangon with a focus on the most densely populated satellite township and adjacent rural communities expected to urbanize and undergo an energy transition in the near future. In doing so, we provide a neighborhood level assessment of energy access and energy transitions in some of the most vulnerable and dynamic communities in Myanmar including urban neighborhoods with migrants and informal settlers, and rural dwellers whose livelihoods are at risk.

In our urban sample, we found considerable heterogeneity in energy access. The overall grid access rate for urban households in our study population is 84%, which was slightly lower than the national urban average at 91% reported in the 2019 Inter-censal Survey [39]. At the ward level, the lowest rate of grid access was in Yeokkan (Site 2). As a result, 54% of Yeokkan households used solid fuels for cooking, compared to about 21% in the other two urban wards. A 2015 study in a neighboring satellite township, Shwepyitar, found nearly 60% of the 150 randomly selected households were using solid fuels as primary fuel for cooking [66]. This suggests that solid fuel use could be contributing to higher household air pollution exposures and localized ambient air pollution [67,68], especially in satellite townships where there is limited access to clean energy.

Despite the high grid access rate of over 96% in the other two urban wards, exclusive use of clean fuels for cooking and lighting remained relatively low. We attribute this in part to low quality and reliability of urban grid electricity supply [69] as confirmed by the World Bank's Multi-Tier Framework (MTF) Survey results [70]. An estimated 15% of urban households in the MTF sample are in Tier 2 or below for electricity access [70], meaning that electricity is available for limited hours during the day or evening, and households are able to use only low-load appliances, such as televisions, fans, and lights. Although this is much lower than 77% of rural households falling into the Tier 2 category, urban grid challenges may be due to several factors, including the fact that the majority of electricity supplied to Yangon comes from hydropower, which can be intermittent due to seasonal fluctuations in precipitation [71]. Power system loses have also been reported due to old and poorly maintained transmission and distribution infrastructure and theft [71,72].

Unreliable provision from the grid may partly explain high ownership of improved biomass cookstoves (>40%) in two urban wards despite high grid access rate. The MTF survey found that 42% of urban households (versus 90% of rural) are in Tier 2 and below for cooking (e.g., meaning that the primary cooking technologies are traditional/open three-stone fires and basic improved cookstoves) [70]. A study of urban household energy choices in Bauchi metropolis in Nigeria found that frequent power outages lead to fuel stacking of solid and modern fuels [73]. We found similar outcomes with urban households using charcoal for cooking, and candle or battery operated devices for lighting in addition to grid electricity.

In our rural sample, grid access is similar to the national rural access rate of 38% [39], which is striking given its proximity to a major metropolitan area. Despite the lower grid access rate, rural households appear to have better access to cleaner lighting fuels compared to some urban households, particularly low-income and informal residents, many of whom reside in Yeokkan (Site 2). Close to half of rural households own a solar panel, compared to just two percent of urban households. Rural households had a higher percentage of electrical appliances compared to households in Yeokkan (Site 2), including refrigerator (17% vs. 14%) and television (63% vs. 49%) (Table S4). Even in villages with no grid electricity, households reported ownership of electric appliances, including television, electric fan, radio/CD/sound system and VCD/DVD player (Figure S1). Whereas, in Yeokkan (Site 2), many of the informal residents reported use of batteries that can light a bulb for 4 hours every night and are returned to battery charging service provider every morning in exchange for another charged battery to use in the evening.

Among grid-connected households, rural (N = 54) reported more hours of electricity available in a day and in the evenings, experience less voltage fluctuations, and lower frequency and duration of blackouts compared to urban households (N = 380). The 2017 Myanmar MTF Survey also reported rural households experienced better quality (voltage stability) and reliability (frequency and length of blackouts) of grid electricity compared to urban households [70]. We believe the better grid stability in rural areas proximate to Yangon City is due to newer transmission lines (e.g., compared to the older ones that are supplying to Yangon City). In recent years, several new power stations have been installed in rural Yangon. Further, proximity to Yangon City may be a factor in grid stability as the area is not characterized by remoteness or low density of potential customer base, and because the cost of maintenance and repair is relatively low.

Our regression analyses confirm the rural "advantage" with regards to lighting where rural households are over two to six times more likely to be exclusive clean lighting fuel users compared Ward 7 (Site 4), which has the highest grid access rate in our study area. Interestingly, the odds were highest in the villages where there was no grid electricity available (Kyahone, Kyeinpaik, and Chaung-nyiko). We attribute this to high reliance on solar, where 57%-83% of rural households in the three off-grid villages own solar panels (Table S5).

However, we find the rural "advantage" was not consistent across seasons. Our panel analysis found rural households have significantly reduced odds of being a clean lighting fuel user in the monsoon season. We believe this may be due to lower sunlight available during the rainy season to charge solar devices. We also find that a higher proportion of rural households reported voltage fluctuations, and increased frequency and duration of blackouts in monsoon compared to dry season. Rural grid lines may be more vulnerable to extreme weather during monsoon, such as strong winds and falling trees causing poorer quality and reliability of electricity supply. Despite the diminished quality of the grid electricity in the monsoon for rural households, it was still slightly better than or equal to that of urban households, as measured by hours of electricity available in day, voltage fluctuations, and quantity and duration of blackouts.

We find limited LPG usage in both our urban and rural household samples, which are in line with findings from other studies in Myanmar. The 2015 study in the adjacent satellite township of Shwepyitar found 1% of homes owned LPG stoves [66]. The MTF Survey found that 3.4%

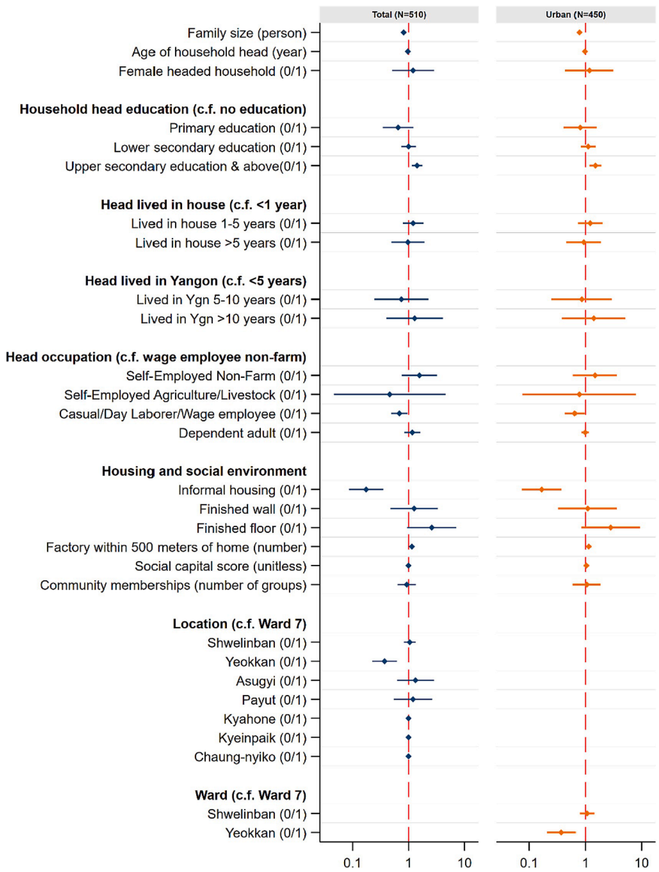

Fig. 6. Odds of exclusive use of clean fuels (electricity/gas) for cooking (dry season). Note. Analysis with rural sample not shown due to small sample size.

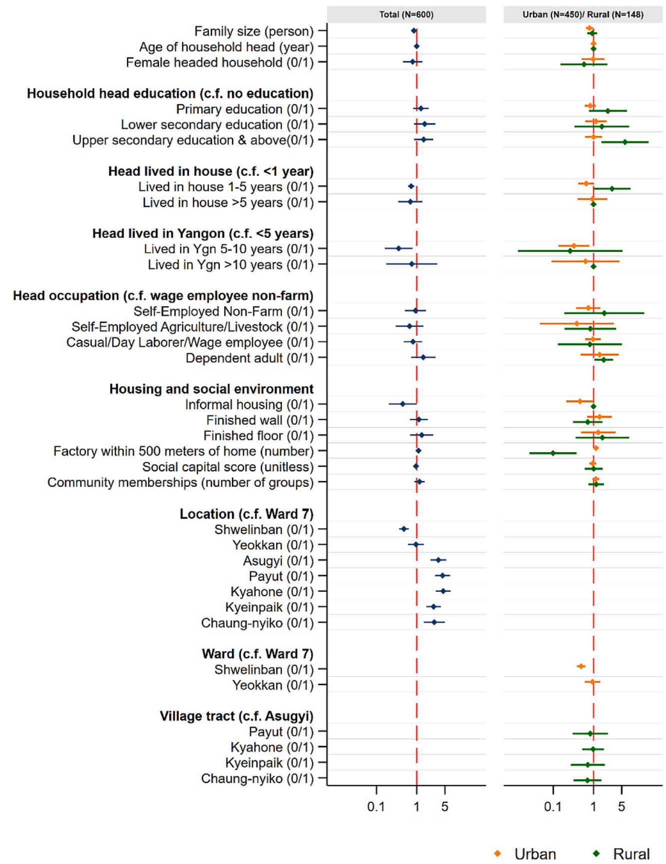

Fig. 7. Odds of exclusive use of clean fuels (electricity/solar) for lighting (dry season).

of urban and 0.1% of rural households used LPG as their primary cooking fuel. Our qualitative interviews revealed a dominant perception among urban households that LPG was dangerous and could lead to explosions, similar to findings in the Shwepyitar Study. Government programs that provide awareness and education around use of LPG stoves as well as financial assistance to help with high start-up costs could increase uptake of LPG and alleviate the health and social burden of biomass fuels for low-income households.

In our analyses of social determinants of energy access, informal status of a household is strongly associated with not having a grid connection after controlling for other socioeconomic indicators. In-depth qualitative interviews support this finding where informal households report their lack of secure tenure and legal recognition by local ward administrators as barriers to obtaining grid connection. Low-income households, many of whom are also informal, report high costs of electricity and gas as barriers. It is important to note that electricity tariffs remain relatively low in Myanmar; over 99% of households report spending<5% of household expenditures on electricity [70]. In our sample, we find that households spend<5% of household expenditures on household energy services, although Yeokkan (Site 2) households spend more but remain under 6%. Our findings are similar to those reported by the Myanmar Living Condition Survey, which found households spend 4% of expenditures on energy [36]. We believe the high cost barriers noted by some of the households are the initial cost of grid connection, or the fixed costs of purchasing clean technologies, such as gas stoves and solar panels. Our findings are similar to those from Shwepyitar, a satellite township adjacent to Hlaingtharya [66], which also found that low-income households who are dependent on battery light are spending more on a monthly basis to light their homes compared to the monthly grid electricity tariffs. However, households continued to use battery light as they could not afford grid connection fees or other improved technologies.

Our findings suggest that energy poverty is persistent for many households depending on residential duration and migration type. For example, households who have lived in Yangon longer (5–10 years) were associated with significantly lower odds of using clean lighting fuels exclusively compared to recent migrants (<5 years). The odds for clean cooking fuel use were also lower for households who have lived in Yangon for five or more years, although the results were not statistically significant. The persistence of energy poverty for longer-term residents, or the reason for recent migrants having better access to clean household fuels may be due to distinct migration patterns in Yangon. The more recent migrants (<5 years) are more likely to be factory workers moving to Yangon as a result of recent economic and industrial expansions in satellite towns in the outskirts of Yangon City [52]. Many of them are women, who work in garment factories, and live in dorms or apartment buildings already connected to the grid. They are also likely to have migrated from other urban areas, and therefore, may have more familiarity with modern energy fuels.

Less recent migrants (e.g., 5–10 years) are likely to be those fleeing the devastation of the 2008 Cyclone Nargis where an estimated 140,000 lives were lost in nearby Ayeyarwaddy Region [74]. Many internally displaced persons and whose agricultural livelihoods were destroyed migrated to Hlaingtharya Township in subsequent years [52] and our sample may be capturing a large part of this population in the 5–10 year residence category. Some respondents indicate unfamiliarity with modern cooking fuels, especially gas, and thus are reluctant to use it, as they fear gas cylinder explosions. This perception may be particularly strong among rural migrants, who are unfamiliar with modern household fuels.

Among the urban household sample, female-headed households were associated with significantly lower odds of having grid connection. Still, female-headed households were associated with non-significant higher odds of being an exclusively clean fuel user for cooking, suggesting a desire for clean cooking fuels among women. In the interviews, female biomass fuel users report inconveniences of cooking with charcoal and wood fuels, such as the need to scrub pots dirtied by biomass fuel burning residues, and tending to the fire constantly to prevent potential fire outbreaks. Some of them also report their preference for cooking with electricity due to timesavings from faster cooking and the ability to multitask. We also found rural female-headed households had statistically higher odds of exclusive use of clean lighting fuels, particularly in monsoon. Previous studies have found that modern energy, such as solar lighting, provides more benefits to women and children who spend more time in the house [75]. Our findings suggest that women headed households may have a higher desire to use modern energy fuels.

We highlight four limitations of our study. First, we experienced 29% loss to follow up among urban households between the two waves due to the highly mobile population in our study sample, which includes migrant workers. In the rural areas where the population is more static, only 5% of households were loss to follow up. Given that we do not observe large differences in energy access across seasons, and that our panel analysis yielded similar results with respect to determinants of access, we do feel that our study is representative of the broader population in both time periods. Second, informal status of the household is a sensitive topic. As it is inappropriate to ask the respondent directly about their legal residency status, we asked several questions around ownership of house and land, and taxes paid in order to infer whether the household had informal status. We tried to minimize the classification error associated with informal residential status by triangulating with the field team managers and the ward offices during the survey. For example, house located in a geographic cluster of a squatter neighborhood will be assigned an informal status even it is reportedly paying rent to its owner. Third, this is an observational study. Our aim is to find associations and does not claim to draw causal inference. Lastly, our qualitative analysis includes interviews with 20 households and was restricted to urban neighborhoods. New themes may emerge with a larger sample size and inclusion of rural households. Our primary focus was to understand the lived experiences of the urban poor and the challenges they face with energy access. Our approach is limited to insights relevant to urban households with an emphasis on those classified as informal settlers.

5. Conclusion

Our study highlights heterogeneity in urban energy access in LMICs, a topic that has had limited attention, particularly in relation to both structural and social determinants including limitations with grid supply, seasonal variation, informal status, migrant status and duration, and gender. Our main contribution is to illuminate heterogeneity in energy access, and by extension energy poverty, within a relatively small but extremely population dense urban area. We also compare energy access in adjacent urban and rural sites, highlighting missed opportunities for low-income urban households that could benefit from adopting solar systems for some household energy services as many rural households lacking grid access have done. Our mixed-methods investigation allows for a more nuanced understanding of drivers and barriers to improving energy access and the persistent nature of energy poverty for marginalized urban communities. Finally, the comparison of adjacent communities at varying stages of urbanization provides a glimpse of what energy transitions look like in rapidly urbanizing LMICs; our use of space for time substitution allows for a more robust analysis of energy transitions than traditional rural/urban comparisons.

We present these results at a time when the world is reeling from health, social and economic impacts of the COVID-19 pandemic. Many urban populations in LMICs are expected to fall into extreme poverty as a result of high unemployment and sharp falls in income during the COVID-19 crisis [76]. Given the strong positive correlation between poverty and energy poverty [77], these conditions are likely to exacerbate urban energy poverty in LMICs. There is evidence emerging on the backtracking of progress made in modern energy access in Nairobi where urban informal households are found to be switching from gas to solid fuels for cooking due to reduced income [78,79]. Similar time-sensitive research is critical for understanding the extent of impacts for low-income urban populations to inform appropriate intervention policies and programs.

Research and policy attention to urban energy access is needed as the world's slum population is expected to increase with growth of urban population primarily in low-income countries. Our study informs knowledge gaps in energy access for the urban poor in one of the poorest countries in Asia. We recommend that urban planners and policy makers quickly address energy access issues for the increasing informal settlement population in Yangon including legal residential recognition so households can apply for grid connection. Even if legal residency is provided, low-income households may not be able to afford electricity [28]. Financial assistance to access cleaner energy, such as grid electricity, solar panels, and LPG, particularly for low-income and women-headed households could help reduce inequities. Training and awareness on safe use of LPG could help alleviate the perceived burdens associated with solid fuels use. There are electrification initiatives in slums that have helped marginalized populations connect to modern fuels [80], which should also be considered in Yangon. Though Myanmar's recent political events in 2021 are likely to hinder progress, we expect that this study's findings will be relevant for rapidly urbanizing cities in other LMICs.

We recommend further research on urban energy access and the causes of persistent energy poverty with a goal to improve energy access for growing populations in LMIC cities. Additional research at the intersection of migration to urban areas and access to public services (energy, water, healthcare, education) could provide important evidence for LMIC policy makers and urban planners. For example, our study found that migrants who arrived in Yangon in the past 5–10 years believed to be as a result of Cyclone Nargis fare worse in energy access compared to recent residents who migrated for factory jobs. Given the increasing frequency of extreme weather events globally due to climate change, mass displacement of populations is expected. In addition, research that can provide additional insights into role of gender in urban energy access would fill knowledge gaps [81], and help inform interventions specific to the urban context. Finally, we call for more research that compares rural and urban sites in close proximity to one another, as there are exciting opportunities in these spaces to learn about energy transitions. Of particular interest are rural areas expected to transition to *peri*-urban or urban areas in the short run.

The issue of urban energy poverty is growing in salience as cities in LMICs undergo significant demographic shifts. Today, over half (55%) of the world's population live in urban areas, and the proportion is predicted to increase to 68% by 2050, with most of this growth concentrated in cities in LMICs [19]. Further, a quarter (one billion people) of the global urban population lived in slums in 2018 and this is expected to grow to three billion, or 30% of projected population growth by 2050, primarily in Asia and Africa [82]. It is expected that the population who lack access to modern energy will grow significantly in these regions. At present three-quarters of global energy use takes place in urban locations [20], making the challenge of meeting future urban energy needs increasingly urgent.

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.2021.102432.

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