Does location matter? Investigating the spatial and socio-economic drivers of residential energy use in Dar es Salaam

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Abstract

Africa is set to become a key contributor to global energy demand. Urban growth and the energy use of city residents will drive much of the region’s changing energy picture. However, few studies have assessed residential energy use among African cities, and the heterogeneity in energy use at the sub-city scale. We use the case of Dar es Salaam, which is among Africa’s fastest-growing cities, and to our knowledge, present the first disaggregated estimates of residential energy use at the ward level. We show three main findings. First, we find a statistically significant difference in mean residential energy use among the surveyed wards, which group into four clusters representing distinct levels of household and transport-related energy use. These results show that mean residential energy use (the sum of household and transport-related energy use) is not always correlated with the socio-economic or spatial characteristics of wards—e.g. Msasani (high-income, formal ward) showed similar residential energy use as Keko (low-income, informal ward). Second, we show differences in energy use and fuel switching that occur between low-income and high-income wards: wood fuel (i.e. charcoal) is a majority contributor to residential energy use in low-income wards (Buguruni, Keko and Manzese), compared to gas, electricity and transport oils in high-income wards (Msasani and Kawe). Finally, regression models indicate that ward density has a statistically significant effect on transport-related energy use, while fuel stacking and proxies for household wealth have a statistically significant effect on household-related energy use. To conclude, we recommend that policymakers account for ward level differences in residential energy use when crafting energy sector strategies for Dar es Salaam (e.g. electrification, energy-efficient cooking, or public transportation initiatives). Policymakers may also anticipate possible convergence towards higher levels of energy use and a shift towards modern fuels, as wards develop socio-economically over time.

1. Introduction

Current literature presents few examples of the energy use of African cities at the sub-city scale (i.e. the settlement or ward level). The Africa region accounts for only 5% of global energy demand (IEA 2014), and 3.7% of (2018) global energy-related greenhouse gas (GHG) emissions (IEA 2019a). However, urbanization and economic activity in the region could increase future energy use and GHG emissions to reach as high as 20% to 23% of global emissions in 2050 (Lucas et al 2015, Calvin et al 2016), equivalent to the current (2017) emissions of the United States and Canada (IEA 2019b). Despite these staggering trends, most regional studies only quantify energy and/or material use (e.g. water and waste consumption) at the aggregated city scale (e.g. Currie et al 2015, Currie and Musango 2017, Hoekman and von Blottnitz 2017, Olaniyan et al 2018), and generally, studies have drawn two main conclusions. First, that estimated national or city-level electricity use is strikingly low vis-à-vis developed countries, e.g. between 90 and 135 kWh per household per month in Nigeria (in 2017) (Olaniyan et al 2018), compared to 909 kWh per household per month in the United States (in 2018) (EIA 2018). Second, there are wide disparities
in energy use within and between African cities, e.g. between rural and urban areas (Olanian et al 2018, Roy Chowdhury et al 2019), or high-GDP and low-GDP cities (Currie et al 2015). Relatedly, some studies that have disaggregated energy use at the sub-city level (e.g. Hughes-Cromwick 1985, Roy Chowdhury et al 2019, Smit et al 2019, Strydom et al 2020) highlight the inequalities in infrastructure access for different population groups, and the low energy use of informal settlements (which are sometimes the most deprived settlements though constitute most urban residential land-use). However, how energy use varies across different settlement types (e.g. between formal or informal settlements) is largely unknown, and could result in policy measures that do not consider the local reality, i.e. the heterogeneity that may exist between settlements (and populations) of differing socio-economic status, or spatial location within an individual city.

This study broadly addresses these existing data gaps. Specifically, we elucidate the spatial and socio-economic drivers of residential energy use that could be considered in the advancement of energy policies in Dar es Salaam, which is among the fastest growing cities in Africa, alongside Lagos, Lusaka and Accra, among others (UN 2018). If policymakers understand the heterogeneity in energy uses that exists between populations, this could inform different approaches to implementing policy visions at the settlement level. Current literature on urban infrastructure in Africa has shown that centralized structures of service delivery (e.g. via state-led utilities) often do not result in equal access to services for the poor. For example, studies have highlighted inequalities in the delivery of water and sanitation services in Dar es Salaam (Monstadt and Schramm 2017) and Kampala (Uganda) (Lawhon et al 2018), or electrification in Accra (Ghana) (Silver 2015), Cotonou (Benin) and Ibadan (Nigeria) (Rateau and Jaglin 2020). Authors of these studies have also highlighted the broader societal and urban governance factors that influence service delivery, and the need to integrate ‘hybrid’ or ‘decentralized’ solutions to ensure more equitable infrastructure configurations, e.g. engaging informal service providers or local communities in the provision of services. However, authors—particularly energy-specific studies of Silver (2015) and Rateau and Jaglin (2020)—did not quantify differences in electricity or energy use (e.g. kilowatt hours (kWh) of electricity, or gigajoules of energy per household) as we do in this current study.

We assume that high rates of urbanization and economic growth projected for Dar es Salaam (UN 2018) could play a role in driving future energy convergence, as historically observed in China (Fan et al 2017) and India (Chaturvedi et al 2014), for example. Therefore, by quantifying energy uses at the settlement level, policymakers could anticipate future changes and differences in demand, e.g. if lower consuming settlements catch up to the per capita rates of higher consuming ones. Similar trends could unfold at the aggregated city level in Dar es Salaam, and the sub-city (ward) data presented in this study could predicate possible changes at the settlement level. For example, a more rapid increase in energy use could be expected among low-income wards that become more developed over time, compared to a gradual and slower increase in energy use among high-income wards due to their evolving consumption structure, e.g. from wood fuels (charcoal and firewood) to modern fuels (electricity or transport oils).

Our study focuses on residential energy use, which accounts for most of Tanzania’s energy demand (70% as of 2017, IEA 2019c). Specifically, we focus on (a) total residential energy use, (b) cooking fuels, and (c) transport energy. There are several factors that are likely to drive large changes in these specific categories. To begin, Tanzania has an ambitious policy vision to develop their energy sector, including access to reliable, affordable and efficient energy for all (Government of Tanzania 2015a, 2015b). Improved access will drive higher residential energy use and GHG emissions (Luo et al 2020), which would require clear understanding of ward level differences to manage these possible changes. The country’s action agenda (Government of Tanzania 2015b) promotes universal access to modern cooking solutions by 2030, i.e. replacing wood fuels (charcoal and firewood) with electricity or liquefied petroleum gas (‘gas’) to promote the sustainable use of wood fuels and alleviate their associated health burdens (e.g. from indoor air pollution). In 2018, wood fuels accounted for 93% of energy used for cooking by Tanzanian households. This can be compared to only 5% from gas, 1% from kerosene, and 1% from electricity (IEA 2019a).

In transportation, rising private vehicle travel and urban wealth will contribute to higher transport energy in Dar es Salaam (Luo et al 2020). As of 2015, the local ‘dala-dala’ minibus accounted for most passenger trips given its high use among the city’s low-income population (though is characterized by poor service quality). Improvements to the public transport network are currently underway, largely through the city’s bus rapid transit (BRT) system, to attract broader use from different population segments (Government of Tanzania 2017a).

To realize our stated research goals, we examine:

- Differences in residential energy use (i.e. the combined energy use from household and transport-related activities) between selected formal, informal, and mixed wards of Dar es Salaam.
- The statistical relationship between: (a) ward type and residential energy use, (b) cooking fuel choice and household-related energy use,
(c) public transport use and transport-related energy use, and (d) other spatial and socio-economic factors (e.g. land-use, ward density and wealth) and household-related and transport-related energy use, respectively.

This work builds on prior studies (e.g. Lee 2013, Sun et al 2014, Mulenga et al 2019, Mensah and Adu 2015, Sakah et al 2019) that have similarly examined the statistical relationship between household energy use and/or cooking fuel choices and their socio-economic and spatial profiles (e.g. expenditure, income, education, location and infrastructure access) in other countries. For example, Lee (2013) examined the effect of household expenditures, location (rural or urban area), education and water access levels on household electricity, kerosene, and wood fuel use in Uganda. In Ghana, Mensah and Adu employed similar methods as Lee (2013) but did not include electricity use or water access as variables in their analysis (Mensah and Adu 2015).

In the case of Dar es Salaam, available estimates for residential energy use (e.g. electricity, gas, or charcoal access or use) are mostly aggregated at the national or city level. For example, electricity access estimates for Dar es Salaam in the 2016 ‘Energy Access Situation Report’ (Government of Tanzania 2017b) encompass the city’s five major districts (data at the ward level are not provided). To our knowledge, studies have not disaggregated energy uses across different settlements in Dar es Salaam or other Tanzanian cities, though data are available at the settlement level for other African cities, e.g. electricity use patterns in Johannesburg (South Africa) and Ndola (Zambia) (Roy Chowdhury et al 2019), and household energy use in Nairobi (Kenya) (Hughes-Cromwick 1985). Therefore, our current study offers possible insights to the different energy behaviours of Dar es Salaam residents, and the spatial and socio-economic drivers that could be considered when implementing energy policies in the city.

2. Methods

2.1. Study region

Dar es Salaam is the largest city (and one of 31 administrative regions) in Tanzania (World Bank 2019). It is a port city, located along Africa’s eastern coast, and a major hub for international trade. The metropolitan area, i.e. the ‘Dar es Salaam region’, has a population of 6.1 million (as of 2018), which accounts for 32% of Tanzania’s total urban population (World Bank 2018). The city’s population is estimated to more than double in size by the year 2050, i.e. to between 15 and 16 million in 2050 (Luo et al 2020). At the sub-city scale, the Dar es Salaam region is subdivided into 90 wards (NBS 2013), situated within larger districts (of which there are five: Ilala, Kinondoni, Temeke, Ubungo and Kigamboni). Wards consist of ‘informal’, ‘formal’ or ‘mixed’ settlements, containing various low, middle and high-income households. The term ‘informal’ refers to the nature of land tenure, where land and home ownership is organized privately between individuals without regulation by local or national government (Kironde 2000, Lupala 2002). Such activities are regulated by government in formal settlements. Mixed settlements contain both formal and informal areas within the same sub-city boundary.

Among other socio-economic factors, our study considers the influence of the city’s BRT system that began operation (i.e. phase 1) in 2016. The system has received widespread recognition globally (e.g. ITDP 2017, World Bank 2017, 2019) given the few examples of successful BRT operations in African cities (not including Johannesburg and Cape Town). The phase 1 line operates along 21 km of road, carries 160 000 passengers a day on average (ITDP 2017), and traverses the north-west segment of the city, i.e. Kimara to Kivukoni along Morogoro Road, shown in figure 1. The completed system is expected to cover 137 km of road, to be built in six sequential phases; as of June 2020, construction and tendering for phases 2 and 3 (44 km) is underway (DART 2020).

2.2. Methods overview

At a very high level, we:

(a) Conducted fieldwork to collect household level energy use data across eight wards in Dar es Salaam.
(b) Estimated mean residential energy use (i.e. in GJ HH$^{-1}$ yr$^{-1}$), including disaggregated household and transport-related energy use, in the surveyed wards.
(c) Employed analysis of variance (ANOVA) to test the effect of ward type and cooking fuel choice on mean residential and household-related energy use, respectively.
(d) Employed multivariate ordinary least squares (OLS) and Tobit regressions (coupled with principal component analysis (PCA)) to model the statistical relationship between cooking fuel choice, public transport use, and other spatial and socio-economic factors on household-related and transport-related energy use, respectively.

2.3. Description of fieldwork

Fieldwork was conducted in Dar es Salaam between August and November 2018. A prior fieldtrip was organized in 2017 for early pilot testing of the survey/questionnaire. A ten-person field team was recruited by the authors through in-person interviews in August 2018 (more details in the supplementary material, S1 (available online at stacks.iop.org/ERL/16/024041/mmedia)). In total, surveys were completed for 1363 households across a
socio-economically and spatially diverse set of wards (eight wards in total, which represented 9% of all wards in Dar es Salaam). Ethics clearances received for the study are outlined in the supplementary material, S2. Table 1 summarizes key socio-economic, spatial and sampling data for the surveyed wards.

2.4. Sample design and survey method

Households were selected through stratified sampling where the total number of households surveyed in each ward correlated with the total ward population, i.e. more populous wards accounted for a larger portion of the sample. Households were also selected based on their distance (i.e. near or far) from the city center ('Kivukoni'), and the closest stop along the BRT line (table 1). Figure 1 presents the spatial distribution of the surveyed wards relative to the city center and the BRT line.

Households were randomly sampled via door-to-door street canvassing. Street Chairmen, known locally as ‘Mwenyekiti wa Mtaa’ (who were elected and trusted community leaders), introduced the field team to interview participants prior to each interview. Interview participants included consenting adults (household members) with the capacity to respond to the survey questions. Only consenting individuals who could report on household member composition, energy needs and activities, and weekly commuting patterns, were selected.

The survey was administered digitally via android tablets that were configured with locational features (GPS) for storing geo-spatial data at the ward level, i.e. the location of each surveyed household, street names, and travel destinations. Survey questions were sectioned as follows (full question set in the supplementary material, S3):

- Demographic and household information, including the number of household members, education levels and living arrangements (e.g. single or shared household).
- Locational data, e.g. household location, trip routes and destinations.
- Fuel consumption estimates, e.g. charcoal, gas and electricity use.
- Cooking fuel choices, e.g. with charcoal, gas and/or electric stove.
- Electric appliance ownership e.g. washing machine, refrigerator, television, among other regular household appliances.
- Travel mode choices, e.g. private vehicle (including Uber or Taxi) and/or public modes such as the BRT, ‘dala-dala’ (local minibus), ‘boda’ (motorcycle), ‘bajaji’ (tricycle). The dala-dala, boda and bajaji operate within an informal network where transit routes and use fares are not institutionalized at the city level (Government of Tanzania 2017a).

Figure 1. Map showing surveyed wards in the Dar es Salaam region relative to the city center and BRT line (phase 1).
Table 1. Socio-economic, spatial and sampling data for surveyed wards in the Dar es Salaam region.

| Ward  | Type       | Density (persons km\(^{-1}\)) | Economic bracket | Mean distance of surveyed households to closest BRT stop (km) | Mean distance of surveyed households to city center (km) | Total number of households surveyed |
|-------|------------|-------------------------------|------------------|-------------------------------------------------------------|----------------------------------------------------------|------------------------------------|
| Msasani | Formal\(^a\) | 4402                          | High-income      | 3.4                                                         | 7.3                                                       | 94                                 |
| Sinza | Formal     | 12 151                        | Middle-income    | 1.1                                                         | 8.8                                                       | 111                                |
| Buguruni | Informal\(^c\) | 20 460                      | Low-income       | 3.1                                                         | 6.0                                                       | 242                                |
| Keko  | Informal   | 24 179                        | Low-income       | 1.6                                                         | 3.5                                                       | 113                                |
| Manzese | Informal  | 38 496                        | Low-income       | 0.2                                                         | 7.8                                                       | 235                                |
| Kawe  | Mixed\(^d\) | 4336                          | High-income      | 7.9                                                         | 13.9                                                      | 178                                |
| Kimara | Mixed      | 5569                          | Middle-income    | 1.7                                                         | 14.9                                                      | 221                                |
| Mwananyamala | Mixed  | 20 409                     | Low-income       | 0.6                                                         | 5.8                                                       | 169                                |

\(^a\)Pilot tests were also conducted in Kijitonyama ward, not included in this table.

\(^b\)A formal settlement contains housing and land obtained through national and local government (Kironde 2000).

\(^c\)An informal settlement contains housing and land obtained through individual (informal) means (Kironde 2000).

\(^d\)A mixed ward contains both formal and informal settlements, with some settlements currently being formalized.

\(^e\)Ward density was determined by the authors in ArcGIS using population data provided in NBS (2013).

\(^f\)At the time of the survey, ward level income data was not available for Dar es Salaam. Due to this, income categories were determined based on anecdotal evidence from the fieldwork, which drew on the perspectives of local researchers and officials with demonstrated knowledge of ward level socio-economic differences.

\(^g\)Mean distances were calculated in ArcGIS based on locational (GPS) coordinates of each surveyed household.

To mitigate possible risks associated with identification, each household was assigned a random household identification number (names and genders of participants were not collected). Only participants that completed the informed consent were interviewed. Finally, if a household was unoccupied at the time of a visit or if a member declined to participate in the survey, then the next closest household was surveyed. In total, 1679 households were visited, with results as follows: 1363 (81%) completed the survey, 210 (13%) were not at home, and 106 (6%) refused to participate.

2.5. Approach to quantifying residential energy use

We use the term ‘residential energy use’ to refer to the sum of energy uses from both household and transport-related activities. Energy use was estimated based on fuel use and travel behaviors reported by the surveyed households.

For household-related activities, this included:

- Kilowatt hours of electricity used per household per year (kWh HH\(^{-1}\) yr\(^{-1}\)) based on pre-paid electricity receipts. In Tanzania, households can purchase pre-paid electricity units to provide electricity for daily, weekly or monthly needs.
- Kilograms of wood fuel (i.e. charcoal) used for cooking per household per year (kg HH\(^{-1}\) yr\(^{-1}\)) based on the number of bag(s) used per day, week or month (in kg).
- Kilograms of gas used for cooking per household per year (kg HH\(^{-1}\) yr\(^{-1}\)) based on number of cylinder(s) used per day, week or month (in kg).

We broadly describe household charcoal and firewood use as ‘wood fuel’ use. However, we do not include firewood use in our estimates for residential energy use. Early pilot tests (in 2017) showed that interview participants were unable to estimate their consumption (i.e. in kg) of kerosene and firewood for cooking. Our previous study, which aggregated consumption (i.e. in kg) of kerosene and firewood from our final estimates would not have a major impact on our results. However, their omission is an important limitation that could be considered in future studies in Dar es Salaam and other African cities.

For transport-related activities, interviewed participants reported on the travel behavior of each household member during an average working day during the week. This included reporting on ‘start’ and ‘end’ points for each trip (including transfer points), travel modes used, and common routes taken (e.g. names of major roads). The trip data was later converted to latitude and longitude coordinates based on locational (GPS) data collected from the survey. Travel routes and trip distances for each household member were estimated and digitized in ArcGIS by
the authors and the support of a GIS consultant. Note, we did not incorporate questions on vehicle fuel use (e.g. diesel or gasoline) and efficiency in the survey as respondents were unable to answer these questions during pilot tests. Vehicle fuel use and efficiencies (by travel mode) were determined based on World Bank (2016) data.

The supplementary material (S4) outlines equations used to estimate annual energy use from household and transport-related activities (in GJ HH\(^{-1}\) yr\(^{-1}\)), respectively. Table S1 summarizes the fuel conversion factors applied in this study.

### 2.6. Statistical methods

#### 2.6.1. Analysis of variance

One-way ANOVA tests were applied to determine whether there was a statistically significant effect of (a) ward type on mean residential energy use, and (b) cooking fuel choice on household-related energy use. Where there was a statistically significant effect, post-hoc tests, i.e. Fisher’s least significant differences (LSD) test, were applied to determine which sample groups were statistically different.

#### 2.6.2. PCA

Due to privacy concerns raised during initial pilot tests, we were unable to collect data on household income (i.e. average earnings per household). Instead, we relied on other indicators (or proxies) for wealth, based on data collected from the survey (table 2). We employed PCA to reduce these indicators to a smaller set of principal components (or ‘PCs’), while still retaining much of the variation in the original variables (Jolliffe 2002). Landgraf’s ‘Logistic PCA’ package in R was employed given the binary nature of the data, i.e. households responded ‘yes’ or ‘no’ to questions related to household appliance ownership or education. The two PCs (i.e. PC1 and PC2) explained 80.3% of the deviance in the original model (Jolliffe 2002) recommends a cut-off of between 70% and 90%). We interpret the PC loadings, shown in table 2, in two ways. Firstly, PC1 provides a general picture of household wealth, and households could be sub-divided based on their position along the PC1 dimension. High loadings on PC1 (e.g. owning an air-conditioning unit, refrigerator) could indicate wealthier households (table 2). For example, households in Msasani and Kawe (high-income wards) reported higher levels of appliance use compared to levels in all surveyed wards and had higher PC1 scores on average (boxplots showing PC scores by ward are shown in S5: figures S1 and S2). We are unable to clearly interpret PC2; note that it may not be strictly related to wealth, given that Msasani and Kawe do not have higher PC2 scores compared to other wards (table 2). However, high PC2 loadings for convenience appliances (e.g. television, electric stove) could indicate a household’s predisposition for these common technologies.

#### 2.6.3. Multivariate regression models

We employed multivariate OLS and Tobit (or censored) regressions to model the influence of socio-economic and spatial variables on household-related and transport-related energy use. The supplementary material (S6) provides a description of data variables used in both models. Similar to the study of Lee (2013), we conducted OLS and Tobit regressions to model variable relationships. Household PC1 and PC2 scores were also applied as independent proxy variables in an attempt to control for household wealth, which resulted in improved regression results, i.e. coefficients for PC1 and PC2 showed a statistically significant and positive correlation with both household-related and transport-related energy use (details in tables 4 and 5). Comparative results with the seven original variables applied as independent proxy variables are shown in the supplementary material (S10), where, in some cases, there was no discernable relationship between the original variables and household-related or transport-related energy use, respectively.

### Table 2. PC loadings on variables associated with household wealth. Household responses were binary in nature, where households indicated ‘yes’ (coded as 1), or ‘no’ (coded as 0) in their responses. PC loadings are compared with the proportion of the surveyed households that responded yes, for the entire sample, and for households in Msasani and Kawe (the two high-income wards).

| Variable                  | PC1     | PC2     | Proportion (%) of all surveyed households | Proportion (%) of surveyed households in high-income wards (Msasani and Kawe)* |
|---------------------------|---------|---------|-------------------------------------------|---------------------------------------------------------------------------------|
| 1. Air-conditioning unit  | 0.51    | −0.35   | 11%                                       | 53%                                                                              |
| 2. Refrigerator           | 0.45    | 0.21    | 60%                                       | 94%                                                                              |
| 3. Washing machine        | 0.32    | 0.19    | 9%                                        | 41%                                                                              |
| 4. Electric stove         | 0.24    | 0.46    | 12%                                       | 46%                                                                              |
| 5. Television             | 0.16    | 0.57    | 80%                                       | 94%                                                                              |
| 6. Private vehicle        | 0.41    | 0.08    | 25%                                       | 56%                                                                              |
| 7. Tertiary education     | 0.41    | −0.51   | 39%                                       | 84%                                                                              |

| Cumulative percentage (%) of total deviance explained | 80.3% |

*Full summary statistics for other wards in the supplementary material, S7: table S3.

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The Tobit model was left-censored at zero, which allowed for the regression to inherently account for data clustering at zero (as some households reported zero household-related or transport-related energy use i.e. they did not cook at home or use motorized transport). The OLS model did not account for this data clustering (i.e. the regression incorporated households with zero values within the regression), which may have influenced biases in results. By applying both models, we account for these model differences and comparatively assess findings.

3. Results and discussion

3.1. Differences in residential energy use across the surveyed wards

Boxplots presented in figure 2 show the variation in energy use at the ward level from all activities (i.e. residential energy use) and separated household-related and transport-related activities, respectively. Across all surveyed wards, we estimate mean residential energy use (Plot A) at 38 GJ HH\(^{-1}\), ranging from approximately 30 GJ HH\(^{-1}\) at the lower-bound (Buguruni, Kimarra, Manzese and Sinza) to 50 GJ HH\(^{-1}\) at the upper-bound (Kawe, Keko and Msasani). Disaggregated data summaries for all wards are indicated in the supplementary material, S7. Other notable information is that: (a) all wards have some households with near-zero residential energy use; (b) all wards have substantial overlap in their ranges; (c) high-income wards (Msasani and Kawe) have larger interquartile ranges, where the upper quartile is even more skewed compared to other wards and relative to their medians; and (d) all wards exhibit a right skew, i.e. means are greater than medians, and there are several high-end outliers.

![Figure 2](image-url)
Figure 3. Results from post-hoc tests (i.e. Fisher’s LSD) showing ward level differences in residential energy use (at a significance level of 5%). Wards are ordered according to their mean residential energy use i.e. high, medium-high, medium-low and low residential energy use. Wards shown in the same circle or intersection have no significant differences between them.

Mean household-related energy use ranges between 20 GJ HH\(^{-1}\) (Kimara) and 40 GJ HH\(^{-1}\) (Kawe and Keko) across our surveyed wards (data ranges are wide and right-skewed, i.e. mean values are higher than medians, and there are several high-end outliers) (figure 2, Plot B). Our estimates are higher than averages reported for Global South cities in Asia (e.g. 21 GJ HH\(^{-1}\) in Jakarta (Surahman and Kubota 2018) and 9.6 GJ HH\(^{-1}\) in Nepal (Shahi et al 2020)), but lower than those in North America (e.g. 105 GJ HH\(^{-1}\) in Canada (Statistics Canada 2011), and 101 GJ HH\(^{-1}\) in the United States (Nakagami et al 2008)). Notably, however, we find that some households use energy at rates comparable to or exceeding the averages in North America (see outliers in figure 2, Plot B). Across the surveyed wards, between 1% (Kimara) and 10% (Kawe) of households already exceed the average household energy use in the United States.

Data ranges for transport-related energy use are narrower (figure 2, Plot C), due to several households having an absence of motorized travel (i.e. by private vehicle or public transport). Excluding Kawe and Msasani, we estimate near-zero values for mean and median transport-related energy use (and zero interquartile ranges). However, wide disparities are present within and between wards (shown as outliers, figure 2, Plot C). Similar trends exist when the cumulative share of transport-related energy use is plotted against the cumulative share of all surveyed households (supplementary material, S12), where consumption is unequally distributed towards a few (possibly wealthier) households.

3.2. Effect of ward type on residential energy use
ANOVA test results show a statistically significant effect of ward type on mean residential energy use \(F(7, 1355) = 9.4, p < 0.01\), i.e. there is a statistically significant difference in mean residential energy use between wards. We cluster wards into four categories of residential energy use (‘high’, ‘medium-high’, ‘medium’, and ‘medium-low’ consumers, shown in figure 3) based on results from post-hoc tests (i.e. Fisher’s LSD, which confirmed where the statistical differences occurred between groups). In some cases, we find no statistically significant difference in mean residential energy use between formal and informal wards, or high-income and low-income wards (illustrated in figure 3), e.g. Msasani (high-income, formal ward) and Keko (low-income, informal ward) both have a ‘medium-high’ level of energy use relative to other wards.

Figure 4 illustrates the relative shares of total residential energy use by fuel category, i.e. wood fuels (charcoal), electricity, gas, and transport oils (gasoline and diesel), which vary based on ward type. For example, in low-income wards (Buguruni, Keko and Manzese), wood fuels account for most residential energy use (over 80%). In high-income wards (Msasani and Kawe), modern fuels (electricity, gas and transport oils) account for larger shares (over 50%). Our findings are consistent with other studies in the Africa region that have similarly shown higher wood fuel use among low-income households. For example, the historic study of Hughes-Cromwick (1985) disaggregated urban household energy use (by income group) among surveyed households in Nairobi (Kenya). The study found that wood fuels (charcoal) accounted for most residential energy use among low-income households, i.e. 89% of households in the lowest income group used wood fuels for cooking compared to 31% in the highest income group (Hughes-Cromwick 1985). More recent studies for South Africa (Bohllmann and Inglesi-Lotz 2018), Uganda (Katutsi et al 2020) and Zambia (Mulenga et al 2019) similarly found higher use of wood fuel among surveyed low-income households. However, distinct from the current study, the authors of these studies did not include transport energy in their estimate for residential energy use.
In transportation, we find that private vehicle travel accounts for most transport-related energy use, which could indicate underlying disparities in ward-level transport options. This is further illustrated in figure 5, which shows the relative share of transport-related energy use by mode (Plot A) compared to the total number of households that reported the use of a private vehicle (Plot B). Disparities are most striking in informal (low-income) wards, where the few households that used a private vehicle (5% or less) contribute 50% to 80% of transport-related energy use. Furthermore, energy use in transportation is the most unequally distributed across surveyed households. Adapted Lorenz curves showing inequalities in energy use yield the highest inequality measure (Gini coefficient) for transport-related energy use (see supplementary material, S12). For example, we estimate a Gini coefficient ($G_e$) of 0.87 for transport-related energy use (where $G_e = 1$ indicates the highest level of inequality), compared to 0.38 for household-related energy use (S12). Comparing our results with other global regions, we find similar differences: e.g. 0.407 for China (total household energy use (Wu et al. 2017)), 0.87 for Kenya (electricity use, Jacobson et al. 2005), and 0.14 and 0.28 for Canada (electricity and gas use, Mirnezami 2014).
Table 3. Results from LSD test results showing differences in mean household-related energy use based on household cooking fuel choice among surveyed households in the Dar es Salaam region. 'A' represents the high energy using groups, and 'E' the lowest. Surveyed households grouped with the same letter indicate no statistically significant difference between group means.

| Cooking fuel choice | Dependent variable: log(Household) | Ordered groupings | Number (and %) of households surveyed |
|---------------------|------------------------------------|-------------------|--------------------------------------|
| Electricity, charcoal, and other | 4.7 | A | 1 (0.1%) |
| Electricity, gas and charcoal | 3.62 | AB | 43 (3.2%) |
| Charcoal and electricity | 3.59 | ABC | 2 (0.1%) |
| Gas, charcoal and other | 3.47 | ABC | 37 (2.7%) |
| Only charcoal | 3.42 | BC | 305 (22.4%) |
| Gas and charcoal | 3.41 | C | 549 (40.3%) |
| Gas and electricity | 3.35 | C | 73 (5.4%) |
| Charcoal and other | 3.3 | C | 133 (9.8%) |
| Only gas | 2.51 | D | 193 (14.2%) |
| Gas and other | 2.23 | D | 8 (0.6%) |
| Only electricity | 1.37 | DE | 1 (0.1%) |
| Only other | 0.64 | E | 16 (1.2%) |

Significance (ANOVA) \( p < 0.01 \)

*Our dataset included no household reporting of the following cooking fuel choice combinations: (a) electricity, gas and other (i.e. either kerosene or firewood), (b) charcoal and other, and (c) electricity and other.
*Household-related energy use estimates were log transformed to reduce skewness. Note, household-related energy use is estimated based on the sum of energy uses from household charcoal, gas and electricity use.
*Variables with one or more of the same letters are not statistically different from each other.
*Other’ refers to either kerosene or firewood. Note, these fuels are not included in our final estimate for household-related energy use.
*Total households surveyed sum to 1363. Break-down by ward and additional summary statistics in the supplementary material, S9 and S7.

3.3. Effect of cooking fuel choice and other socio-economic and spatial factors on household-related energy use

We find that most surveyed households do not use electricity for cooking despite relatively high electrification levels at the ward level, i.e. between 75% (Buguruni) and 100% (Msasani and Sinza) of surveyed wards were electrified (supplementary material, S7), but only \( \sim 9\% \) of households reported using electricity as a cooking fuel. The remaining 81% used a combination of gas, wood fuels (charcoal) and kerosene as a cooking fuel (table 3). Other studies in the Africa region have likewise shown limited electricity use compared to wood fuels and gas among households in rural and urban areas, e.g. Mozambique (Castán Broto et al 2020), Ghana (Mensah and Adu 2015), Uganda (Katutsi et al 2020), and South Africa (Bohlmann and Inglesi-Lotz 2018). Though a more recent study for Lagos (Edomah and Ndulue 2020) has shown that increases in electricity use for cooking could be anticipated in the near term (i.e. 2020 onwards) due to the coronavirus (COVID-19) pandemic and mandatory stay-at-home lockdowns.

We also find that electrification levels in Buguruni (75%) are consistent with averages for the Dar es Salaam region reported in Tanzania’s energy access report (i.e. 75% in 2016), which is much higher than the national and rural average of 36% and 16% in 2016 (Government of Tanzania 2017b). However, ward level data is not considered in the energy access report and higher electrification levels in other wards (e.g. Msasani) are not adequately considered in reported data. In the supplementary material (S7), we show the different sources of electricity among electrified households, i.e. between 72% (Buguruni) and 100% (Msasani and Sinza) received electricity from the grid, 0% (Buguruni) and 25% (Msasani) from community or private generators, and 0% (Mwananyamala) and 5% (Kawe) from solar panels. Note that these ranges do not add to 100% as some households reported multiple sources of electricity supply.

Across all surveyed wards, 62% of households fuel stacked, though, with some variation at the ward level (see the supplementary material, S7, for data summaries by ward). Households that fuel stack (i.e. use two or more fuels for cooking needs) are correlated with higher household-related energy use. ANOVA tests found a statistically significant effect of cooking fuel choice on mean household-related energy use \( F(11,1349) = 59.05, p < 0.01 \). Post-hoc (LSD) tests that map the effect of cooking fuel choice on mean household-related energy use show five groupings of households (A to E) (see table 3). However, note that results in table 3 should not be over-interpreted given the different levels of reporting from households, e.g. in the highest group (A), only one household reported fuel-stacking with electricity, charcoal and ‘other’ (i.e. either kerosene or firewood). Therefore, considering these limitations, we find that households that fuel stack with three fuels (6% of all households surveyed) generally appear to be the highest energy users (table 3, group A). Except for charcoal, using a single fuel (e.g. only gas, or only electricity) is associated with lower household-related energy use.

Results from OLS and Tobit regressions correlate fuel stacking with 35% higher household-related
Table 4. Multivariate OLS and tobit regression results showing the statistical relationship between cooking fuel choice, selected spatial and socio-economic variables, and household-related energy use across the surveyed households in the Dar es Salaam region.

| Independent variable: | Dependent variable: Log(household energy use) | OLS (1) | OLS (2) | Tobit (1) | Tobit (2) |
|-----------------------|-----------------------------------------------|---------|---------|-----------|-----------|
| **Spatial**           |                                               |         |         |           |           |
| Informal settlement   |                                               | -0.023  | 0.058   | -0.025    | 0.057     |
|                       |                                               | (0.065) | (0.076) | (0.065)   | (0.076)   |
| Mixed settlement      |                                               | -0.089* | -0.034  | -0.090*   | -0.034    |
|                       |                                               | (0.051) | (0.059) | (0.051)   | (0.060)   |
| Log(Ward density)     |                                               | 0.086** | 0.149***| 0.086**   | 0.150***  |
|                       |                                               | (0.036) | (0.042) | (0.036)   | (0.042)   |
| **Socio-economic**    |                                               |         |         |           |           |
| Log(Household members)|                                               | 0.214***| 0.362***| 0.215***  | 0.363***  |
|                       |                                               | (0.031) | (0.035) | (0.032)   | (0.036)   |
| PC1                   |                                               | 0.018** | 0.010*  | 0.018*    | 0.010*    |
|                       |                                               | (0.002) | (0.002) | (0.002)   | (0.002)   |
| PC2                   |                                               | 0.007***| 0.013***| 0.007***  | 0.013***  |
|                       |                                               | (0.002) | (0.003) | (0.002)   | (0.003)   |
| **Cooking fuel choice**|                                               |         |         |           |           |
| Only charcoal         |                                               | 2.512***| 2.669***|           |           |
|                       |                                               | (0.142) | (0.150) |           |           |
| Only gas              |                                               | 1.508** | 1.666** |           |           |
|                       |                                               | (0.147) | (0.155) |           |           |
| Gas and electricity   |                                               | 1.904***| 2.058** |           |           |
|                       |                                               | (0.169) | (0.175) |           |           |
| Gas and charcoal      |                                               | 2.413***| 2.571** |           |           |
|                       |                                               | (0.141) | (0.149) |           |           |
| Charcoal and electricity|                                             | 2.243***| 2.398** |           |           |
|                       |                                               | (0.448) | (0.451) |           |           |
| Gas and other         |                                               | 1.475** | 1.635** |           |           |
|                       |                                               | (0.251) | (0.256) |           |           |
| Charcoal and other    |                                               | 2.416** | 2.574** |           |           |
|                       |                                               | (0.147) | (0.155) |           |           |
| Electricity, gas and charcoal|                           | 2.241***| 2.396** |           |           |
|                       |                                               | (0.174) | (0.181) |           |           |
| Gas, charcoal and other|                                               | 2.504***| 2.662** |           |           |
|                       |                                               | (0.170) | (0.177) |           |           |
| Electricity, charcoal and other|                        | 3.961***| 4.119***|           |           |
|                       |                                               | (0.612) | (0.616) |           |           |
| Fuel stack when cooking|                                               | 0.326***| 0.328***|           |           |
|                       |                                               | (0.040) | (0.040) |           |           |
| Constant              |                                               | 0.067   | 1.129** | -0.094    | 1.116***  |
|                       |                                               | (0.357) | (0.378) | (0.362)   | (0.381)   |
| Observations          |                                               | 1363    | 1363    | 1363      | 1363      |
|                       |                                               | (Censored: 14) |         | (Censored: 14) |         |
| Pseudo R² (McFadden)  |                                               | 0.418   | 0.193   | 0.805     | 0.769     |
| R²                    |                                               | 0.411   | 0.188   |           |           |
| Adjusted R²           |                                               |         |         |           |           |

*p < 0.1; **p < 0.05; ***p < 0.01.

Standard error denoted by values in parentheses.

Reference variables not included in table: Formal settlement; Only electricity (for cooking).

‘Other’ refers to either kerosene or firewood. Note that these fuels are not included in our final estimate for household-related energy use.

See supplementary material for: (a) supporting correlation matrix of all data variables (S8), and (b) full-set of results from OLS and Tobit regressions, i.e. including original proxy variables (education and appliance ownership) applied as predictors (S10).

Energy use (i.e. taking the exponent of the coefficient, 0.3, shown in OLS and Tobit models—table 4). Fuel stacking with electricity, charcoal and kerosene/firewood (3% of households surveyed) is correlated with the highest household-related energy use (11 and 13 times more, based on estimated coefficients: 2.5 and 2.7 for OLS and Tobit models, respectively) relative to households that use only electricity (reference case). Finally, changes along PC1 and PC2, which we interpret as wealth and possibly propensity to invest in...
Table 5. Multivariate OLS and tobit regression results showing the statistical relationship between public transport use, selected spatial and socio-economic variables, and transport-related energy use across the surveyed households in the Dar es Salaam region.

| Independent variables: | Dependent variable: Log(transport energy use) |
|------------------------|---------------------------------------------|
|                        | OLS (1) | Tobit (1) |
| **Spatial**            |         |           |
| Informal settlement    | 0.316*** | 0.402***  |
| (0.103)                | (0.145) |
| Mixed settlement       | 0.141*  | 0.148     |
| (0.085)                | (0.118) |
| Log(Ward density)      | −0.197*** | −0.177*   |
| (0.064)                | (0.091) |
| Log(Distance to City Center) | 0.028 | 0.078 |
| (0.088)                | (0.124) |
| **Socio-economic**     |         |           |
| Log(Household members) | 0.119*  | 0.184***  |
| (0.048)                | (0.069) |
| PC1                    | 0.043*** | 0.053***  |
| (0.003)                | (0.004) |
| PC2                    | −0.007*  | −0.005    |
| (0.004)                | (0.005) |
| Use public transport   | −0.130*  | 0.054     |
| (0.074)                | (0.107) |
| Constant               | 2.851*** | 2.053**   |
| (0.682)                | (0.961) |
| Observations           | 1363     | 1363 (Censored: 441) |
| R²                     | 0.326    | 0.703     |
| Adjusted R²            | 0.322    |           |

*p < 0.1; **p < 0.05; ***p < 0.01.

Standard error denoted by values in parentheses.

Reference variables not included in table: Formal settlement.

See supplementary material for: (a) supporting correlation matrix of all data variables (S8), and (b) full-set of results from OLS and Tobit regressions, i.e. including original proxy variables (education and appliance ownership) applied as predictors (S10).

common appliances, respectively, show a significant and positive correlation with household-related energy use. Our findings are consistent with other studies that likewise found positive and significant correlations relating both income and fuel stacking to household energy use and/or fuel choices in Tanzania, e.g. D’Agostino et al (2015), Choumert-Nkolo et al (2019).

3.4. Effect of public transport use and other socio-economic and spatial factors on transport-related energy use

We find a positive and significant correlation between transport-related energy use and the PC1 dimension for wealth (table 5). Msasani and Kawe (high-income wards) contribute the highest transport-related energy use (consistent with their high PC1 scores). Furthermore, using public transport as part of a household’s commuting activities (i.e. either by BRT, dala-dala, baji or boda) is correlated with 13% lower transport-related energy use (for the OLS model. Results were indiscernible for the Tobit model). Public transport use (particularly use of the dala-dala) is higher in informal wards, e.g. 93% of households in Buguruni reported using public transport as part of their weekly commuting, compared to 67% of households in Msasani (supplementary material, S7). To interpret these differences in resident travel behavior, we conducted multinomial logit regressions to assess spatial and socio-economic factors affecting travel mode choice (see supplementary material, S11). Findings suggest that household wealth (assumed based on coefficients along the PC1 dimension of wealth) is significantly and positively correlated with households’ choice to use private vehicles (including taxi or Uber rides) relative to the dala-dala. Moreover, even though the BRT is perceived to be more expensive than the dala-dala (Luo, Jean-Baptiste et al 2020), distance to the city center (Kivukoni) is a key predictor of increased BRT use. Households that are further away from the city center are 17 times more likely to use the BRT relative to the dala-dala (taking the exponent of the coefficient, 2.9. See supplementary material, S11).

Distance from the city center is correlated with higher transport-related energy use, e.g. a 100% increase in distance between residence location and the city center is correlated with 2% and 3% higher transport-related energy (table 5). We also find a negative and significant relationship between ward density and transport-related energy use, where a 100% increase in density is correlated with 19% or
16% lower transport-related energy use. These findings are consistent with other literature that associates higher urban densities with lower transport-related energy use, e.g. Vandeweghe and Kennedy (2007), IPCC (2014), Creutzig et al (2015). However, in the case of Dar es Salaam, higher densities may not directly indicate a sustainable or energy-efficient transport system. Considering the unique context in which African cities are urbanizing, where urban growth is coupled with other challenges, including urban poverty and informality, this negative correlation may be due to other hidden socio-economic factors (e.g. financial constraints that prohibit the use of motorized transport) not explicitly considered in this study. Details on these aspects are beyond the scope of this research and would be an important area of future work.

4. Policy considerations

The results presented in this study are suggestive and causality is not assumed. Considering this context, there are three key findings: (a) there is a statistically significant difference in mean residential energy use among Dar es Salaam wards, where differences are between four distinct clusters of household and transport-related energy use (which we illustrate in figure 6); (b) a shift in fuel consumption, i.e. from traditional (charcoal) to modern fuels (electricity/gas/transport oils), is evident from low-income to high-income wards; and (c) consumption of charcoal (typically present in fuel stacking) and private vehicle use are major drivers of household and transport-related energy use, respectively.

Figure 6 shows mean household-related energy use versus transport-related energy use across the surveyed wards, where we identify four clusters of wards, which represent different levels of household-related and transport-related energy use, respectively: (A) Low-Low (Kimara); (B) Medium-Low (Sinza, Buguruni, Manzese and M wananyamala); (C) High-Low (Keko); and (D) High-High (Msasani and Kawe—the high income wards). This clustering suggests that a possible transition in energy use may occur as wards develop from A to D (figure 6), where convergence towards higher energy use could be expected as more wards consume at levels similar to Kawe/Msasani in the future (and where a switch to more modern fuels could be expected). We also find that fuel stacking plays a critical role in rising energy demand and could be considered in the context of ongoing policy measures promoting electrification and energy efficiency. For example, 100% electricity use, or fuel stacking with electricity and gas, could be encouraged as wards develop socio-economically (e.g. towards D, figure 6) to promote a gradual phase-out of charcoal use. Whereas, 100% gas use, or fuel stacking with gas and charcoal (which is associated with lower energy use than using only charcoal, table 3), could be considered for wards ‘in transition’ (e.g. A to C, figure 6). The use of energy-efficient charcoal and gas stoves, which are already stated as a key consideration in Tanzania’s energy policies (e.g. Government of Tanzania 2015b) could be promoted alongside these differentiated interventions.

In transportation, public transport use, particularly BRT use, could be encouraged in all wards, but more so in wards such as Msasani/Kawe (cluster D) with high levels of transport related energy use due to their higher private vehicle travel (figure 6). Therefore, policymakers would need to balance investments in public transport and the BRT service across a wide range of settlements in the city: (a) to improve access/affordability (especially for informal, low-income wards with limited travel options) and (b) to control transport-related energy use (especially in wealthier wards due to their higher private vehicle use). These efforts could feed into ongoing urban planning policies (e.g. Government of Tanzania 2017a) that already envision an energy-efficient and accessible transport system in Dar es Salaam.

5. Study limitations

We highlight three study limitations linked to our methods and results. Firstly, as stated in the methods, we were unable to collect data on firewood and kerosene use (households were unable to estimate their consumption for these specific categories during pilot surveys in Kijitonyama ward). Therefore, our values for household-related energy use may be under-estimated in some cases. We also did not include weekend or leisure travel in our transportation estimates, even though these may have an effect on transport-related energy use and associated GHG emissions. For example, in their review paper, Czepkiewicz et al (2018) found significant positive correlations between urban density and GHG emissions in transportation when long-distance travel is included in the analysis (i.e. from car weekend trips and international flights).

Secondly, our structured survey did not allow for further analysis of contextual factors (e.g. cultural, or local beliefs) that may influence residential energy use. Therefore, future work could incorporate qualitative methods, e.g. participant observation or ethnographic approaches, as to confirm or validate the data we collected in the structured survey. Except for electricity data that was collected via household electricity bills, charcoal, gas, and transport data were reliant on self-reported data, and surveyed households may have under or over-estimated their energy use or travel behaviors.

Finally, future work may broaden the scope of analysis by (a) tracking changes in residential energy use over time (e.g. to validate our assumptions of energy convergence), (b) conducting similar studies...
Figure 6. Differences in household and transport-related energy use across surveyed wards in Dar es Salaam. The size of bubble indicates average ward density. Surveyed wards map along four major typologies of energy use (based on their mean household-related and transport-related energy use, respectively): (A) Low-Low (Kimara); (B) Medium-Low (Sinza, Buguruni, Manzese and Mwananyamala); (C) High-Low (Keko); and (D) High-High (Msasani and Kawe).

in other cities in Tanzania or African countries to compare research findings, (c) estimating GHG implications of energy use and other environmental impacts (e.g. health burdens associated with air pollution), including geographic mapping to identify settlements or populations that contribute most to urban GHG emissions, and (d) engaging with policymakers to develop strategies to translate our data into meaningful policy actions.

6. Concluding remarks

To our knowledge, we present the first estimates of disaggregated ward level residential energy use for Dar es Salaam. We find a statistically significant difference in energy use among the surveyed wards, which can be grouped into four clusters, each representing distinct levels of residential (household and transport-related) energy use. These findings suggest the need for differentiated approaches to implementing energy policies at the sub-city scale. In addition, we highlight that movement towards higher levels of energy use could be expected with continued urban growth in Dar es Salaam (and possibly, other African cities), e.g. towards Msasani/Kawe levels, or those of outliers shown in figure 2. At the same time, fuel switching towards more modern fuels (especially for cooking, e.g. electricity and gas) could be expected with rising wealth, fuel stacking and travel distances, among other socio-economic and spatial factors, contributing to higher residential energy use. Finally, our calculations show the different household and transport-related drivers of residential energy use at the ward level. However, other contextual factors (i.e. culture, society, and urban governance structures) that influence infrastructure service delivery would need to be considered alongside differentiated policy interventions.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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