

Beyond Household Socioeconomic Status: Multilevel Modeling of Supply-Side Determinants of LPG Consumption among 5,500 Households in Sub- Saharan Africa

Matthew Shupler (✉ m.shupler@liverpool.ac.uk)

University of Liverpool <https://orcid.org/0000-0003-0259-9101>

Judith Mangeni

Moi University

Theresa Tawiah

Kintampo Health Research Centre

Edna Sang

Moi University

Miranda Baame

Douala General Hospital

Rachel Anderson de Cuevas

University of Liverpool

Emily Nix

University of Liverpool <https://orcid.org/0000-0003-3331-2046>

Emmanuel Betang

Douala General Hospital

Jason Saah

Kintampo Health Research Centre

Reginald Quansah

University of Ghana

Elisa Puzzolo

Global LPG Partnership <https://orcid.org/0000-0001-9177-5298>

Bertrand Mbatchou

Douala General Hospital

Kwaku Poku Asante

Kintampo Health Research Centre

Diana Menya

Eldoret

Daniel Pope

University of Liverpool

Analysis

Keywords: clean cooking transitions, primary fuel, stove stacking, liquefied petroleum gas, LPG, cylinder refills

Posted Date: February 9th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-154082/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Nature Energy on November 18th, 2021. See the published version at <https://doi.org/10.1038/s41560-021-00933-3>.

Abstract

Household transition to cleaner cooking fuels (e.g. liquefied petroleum gas (LPG)) has historically been understood as an “energy ladder” with clean energy access resulting from improvements in household socioeconomic status (SES). Recent studies have demonstrated the importance of supply-side determinants in increasing clean cooking, yet few large-scale studies have assessed their significance quantitatively. As part of the CLEAN-Air(Africa) study, a population-based survey was conducted (N = 5,638) assessing cooking practices in peri-urban communities within Cameroon, Kenya and Ghana. Multilevel logistic and log-linear regression were used to assess socioeconomic and supply-side determinants of LPG usage (primary versus secondary fuel) and consumption (kilograms/capita/year), respectively. Supply-side factors (e.g. cylinder refill and transportation costs) and using single versus multi-burner stoves were better predictors of both the probability of primarily cooking with LPG and annual LPG consumption than household SES. These results suggest the need for policies promoting LPG access and stove equipment that meet household needs.

Introduction

Polluting fuels, including biomass (e.g. wood, charcoal), coal and kerosene, are used by approximately 3.8 billion individuals worldwide for cooking, heating and lighting.¹ Household air pollution (HAP) generated from incomplete combustion of these fuels results in fine particulate matter (PM_{2.5}) levels typically well above World Health Organization (WHO) guidelines.² Exposure to PM_{2.5} in HAP is causally associated with many adverse health outcomes, including cardiopulmonary, and respiratory diseases.³⁻⁶ Polluting fuel use also negatively impacts climate through deforestation from unsustainable harvesting of wood in certain locations,⁷ and emissions of short-term climate-forcing pollutants; 25% of global anthropogenic black carbon emissions are produced through household biomass combustion.^{7,8} Women, typically the primary cook, may travel long distances to gather polluting fuels in some settings, which negatively impacts their livelihoods.^{9,10}

In Sub-Saharan Africa (SSA), approximately 900 million people cook with polluting fuels.¹¹ Governments in SSA, including Cameroon, Ghana and Kenya, plan to expand population-level use of liquefied petroleum gas (LPG) as an interim solution for clean cooking to an aspirational target of between 35% and 58% over the next decade.¹²⁻¹⁴ LPG, although a fossil fuel, does not emit black carbon, and has much lower PM_{2.5} emissions than polluting fuels.^{12,15,16} Using LPG for cooking can also decrease localized deforestation, and reduce time spent gathering and cooking with polluting fuels.^{16,17}

Historically, studies focused on determinants of clean cooking have emphasized the ‘household energy ladder’ model, by which improvements in socioeconomic status (SES) lead households to progressively transition to cleaner energy sources.¹⁸⁻²⁰ However, other aspects, including consistent fuel access, safety and convenience are also important facilitators of clean cooking fuel uptake.²¹⁻²³ Studies in India found that rural households provided with subsidies for LPG connections under the Pradhan Mantri Ujjwala

Yojana (PMUY) programme continued to use polluting fuels alongside LPG ('stove stacking'), leading to less frequent LPG use compared with urban households.^{24,25} Reduced LPG uptake likely resulted from poorer supply and access points in rural Indian villages. While studies conducted in Cameroon,^{26,27} Tanzania²⁸ and Ethiopia²⁹ have also found supply-related issues to be important determinants of cooking fuel decisions, few large-scale studies in SSA have quantitatively assessed their effect on LPG consumption.

As partial use of clean cooking fuels (stacked with polluting fuels) does not provide sufficient HAP exposure reductions to benefit health,³⁰ a comprehensive understanding of facilitators for sustained and exclusive LPG use is critical to maximizing health gains. This multinational modeling study of over 5,500 households in peri-urban communities of Mbalmayo, Cameroon; Eldoret, Kenya and Obuasi, Ghana, presents one of the largest assessments of supply-related impacts on LPG fuel usage in SSA. With urban populations in SSA predicted to double over the next 25 years, this analysis provides a timely examination across three rapidly developing communities.

Cooking Environment Characteristics

The final sample included 5,638 households (Obuasi, Ghana:1,987 (35%); Mbalmayo, Cameroon:1,811 (32%); Eldoret, Kenya:1,840 (33%)). Participants that did not cook at home (n=416; 7%) were excluded. The proportion of individuals primarily cooking with LPG varied substantially by community (Obuasi:38% (n=757), Mbalmayo:28% (n=468), Eldoret:5% (n=35)) (Figure 1).

Figure 1. Primary cooking fuel types among three peri-urban communities in Ghana, Cameroon and Kenya

Sixty percent (n=2,772) of households 'stacked' at least two cooking fuels. Fuel stacking was 30% higher among households primarily using LPG (82%) compared with households primarily using polluting fuels (53%). Fuel stacking prevalence among households primarily cooking with polluting fuels was approximately 20% higher in Eldoret and Mbalmayo (60%) compared with Obuasi (40%).

A higher percentage of households primarily cooking with LPG contained a member with a university degree (22%) and were in the highest income quartile (23%), compared with households primarily using polluting cooking fuels (5% with university degree; 8% in highest income quartile) (Table 1). In Eldoret and Mbalmayo, the proportion of households cooking primarily with polluting fuels that reported seasonal changes in income (72% and 75%, respectively) was 20-30% higher than those primarily cooking with LPG (42% and 58%, respectively). Among households primarily cooking with LPG, 59% had fewer than 5 family members, compared with 38% of those primarily cooking with polluting fuels (Table 1).

Table 1. Socioeconomic and cooking environment characteristics of study households (n=4,555)

Characteristic	Overall (N=4555)		Mbalmayo, Cameroon (N=1811)		Obuasi, Ghana (N=1987)		Eldoret, Kenya* (N=757)	
	LPG Primary (N=1260)	Polluting Primary (N=3295)	LPG Primary (N=468)	Polluting Primary (N=1343)	LPG Primary (N=757)	Polluting Primary (N=1230)	LPG Primary (N=35)	Polluting Primary (N=722)
Cooking fuel stacking (%)	1029 (82%)	1743 (53%)	389 (83%)	788 (59%)	610 (81%)	478 (39%)	30 (86%)	477 (66%)
Number of cooking fuels used								
One	231 (18%)	1552 (47%)	79 (17%)	555 (41%)	147 (19%)	752 (61%)	5 (14%)	245 (34%)
Two	875 (69%)	1296 (39%)	264 (56%)	565 (41%)	587 (78%)	398 (32%)	24 (68%)	333 (46%)
Three	106 (8%)	322 (10%)	81 (17%)	130 (10%)	20 (3%)	74 (6%)	5 (14%)	118 (16%)
Four or more	51 (4%)	125 (4%)	44 (9%)	93 (8%)	3 (0%)	6 (1%)	1 (3%)	26 (4%)
Age (Mean SD)	35 (12)	39 (15)	33 (12)	36 (15)	36 (11)	40 (14)	33 (12)	41 (15)
Sex of fuel decision maker (% female)	632 (78%)	1748 (87%)	34 (79%)	116 (85%)	572 (78%)	1006 (84%)	26 (76%)	626 (92%)
Marital status								
Married	609 (49%)	1634 (49%)	147 (31%)	477 (36%)	437 (58%)	632 (51%)	25 (71%)	525 (73%)
Single	394 (31%)	873 (26%)	167 (36%)	455 (34%)	219 (29%)	302 (25%)	8 (23%)	116 (16%)
Cohabiting	184 (15%)	414 (13%)	129 (28%)	288 (21%)	54 (7%)	123 (10%)	1 (3%)	3 (0%)
Widowed	31 (2%)	286 (9%)	20 (4%)	102 (8%)	10 (1%)	114 (9%)	1 (3%)	70 (10%)
Divorced	42 (3%)	88 (3%)	5 (1%)	21 (2%)	37 (5%)	59 (5%)	0	8 (1%)
Home size (# of members)								
1-2					212 (28%)		13 (37%)	
3-4	272 (22%)	380 (12%)	47 (10%)	84 (6%)	297 (39%)	245 (20%)	16 (46%)	51 (7%)
5-6	463 (37%)	865 (26%)	150 (32%)	274 (20%)	196 (26%)	395 (32%)		196 (27%)
7+	338 (27%)	1002 (30%)	138 (29%)	372 (28%)	52 (7%)	374 (30%)	4 (11%)	256 (35%)
	187 (15%)	1047 (32%)	133 (28%)	612 (46%)		216 (18%)	2 (6%)	219 (30%)
Cooking location								
Indoors (separate structure)	98 (8%)	1404 (43%)	71 (15%)	675 (50%)	23 (3%)	105 (9%)	4 (11%)	624 (86%)
Outside (open air)	23 (2%)	512 (16%)	8 (2%)	367 (27%)	15 (2%)	134 (11%)	0	11 (2%)
Veranda/porch	428 (34%)	715 (22%)	0	117 (9%)	428 (57%)	633 (51%)	0	0
Indoors (separate room)	479 (38%)	435 (13%)	253 (54%)	69 (5%)	216 (29%)	328 (27%)	10 (29%)	38 (5%)
Indoors (single room)	212 (17%)	142 (4%)	118 (25%)	75 (6%)	73 (10%)	27 (2%)	21 (60%)	40 (6%)
Heating fuel								
None	757 (60%)	1229 (37%)	465 (100%)	1338 (100%)	757 (100%)	1230 (100%)	15 (43%)	198 (27%)
Manufactured stove	15 (2%)	424 (13%)	0	0	0	0	15 (43%)	424 (59%)
Open fire	3 (0%)	36 (1%)	2 (0%)	4 (0%)	0	1 (0%)	1 (3%)	31 (4%)
Nonmanufactured stove	4 (0%)	70 (2%)	0	1 (0%)	0	0	4 (11%)	69 (10%)
Lighting fuel								
Electricity (grid or solar)	1251 (99%)	2819 (85%)	466 (100%)	1250 (93%)	755 (100%)	1181 (96%)	30 (86%)	388 (54%)
Solar-powered lantern	4 (0%)	230 (7%)	1 (0%)	35 (3%)	0	0	3 (8%)	195 (27%)
Kerosene lamp	3 (0%)	124 (4%)	1 (0%)	36 (3%)	0	0	2 (6%)	88 (12%)

Rechargeable flashlight	0	38 (1%)	0	4 (0%)	0	13 (1%)	0	0
Battery-powered flashlight	1 (0%)	50 (2%)	0	1 (0%)	1 (0%)	35 (3%)	0	14 (2%)
Candle	0	9 (0%)	0	4 (0%)	0	0	0	5 (1%)
Oil or LPG lamp	1 (0%)	9 (0%)	0	1 (0%)	1 (0%)	1 (0%)	0	7 (1%)
Country-standardized HH income quartile								
1 (lowest)	77 (6%)	662 (20%)	13 (3%)	122 (9%)	48 (6%)	133 (11%)	16 (46%)	407 (56%)
2	212 (17%)	558 (17%)	106 (22%)	219 (16%)	102 (13%)	280 (23%)	4 (11%)	59 (8%)
3	329 (26%)	497 (15%)	70 (15%)	111 (8%)	258 (34%)	378 (31%)	1 (3%)	8 (1%)
4 (highest)	293 (23%)	264 (8%)	12 (3%)	6 (0%)	281 (37%)	256 (21%)	0	2 (0%)
Not disclosed/do not know	165 (13%)	710 (22%)	151 (32%)	464 (35%)	0	0	14 (40%)	246 (34%)
Seasonal changes in income								
Yes	799 (65%)	1980 (71%)	270 (58%)	335 (75%)	524 (69%)	821 (67%)	5 (42%)	151 (72%)
Obtain cooking fuels for free								
Yes	53 (4%)	1136 (34%)	33 (7%)	423 (31%)	14 (2%)	245 (20%)	6 (17%)	468 (65%)
Highest HH education level								
No formal education	43 (3%)	246 (5%)	3 (1%)	115 (9%)	40 (5%)	163 (13%)	0	57 (8%)
Primary	108 (9%)	791 (17%)	66 (14%)	722 (54%)	37 (5%)	139 (11%)	8 (23%)	194 (27%)
Secondary/high school	815 (65%)	1706 (37%)	302 (65%)	469 (35%)	508 (67%)	852 (69%)	5 (14%)	132 (18%)
University	272 (22%)	227 (5%)	96 (21%)	26 (2%)	170 (22%)	75 (6%)	6 (17%)	37 (5%)
Main water source								
Well (pit with bucket)	277 (22%)	1333 (40%)	122 (26%)	534 (40%)	134 (18%)	265 (22%)	21 (60%)	534 (74%)
Communal standpipe	444 (35%)	921 (28%)	117 (25%)	307 (23%)	325 (43%)	598 (49%)	2 (6%)	16 (2%)
Pipe in home	472 (37%)	730 (22%)	192 (41%)	344 (26%)	272 (36%)	318 (42%)	8 (23%)	68 (9%)
Pump (deep well)	52 (4%)	165 (5%)	28 (6%)	98 (7%)	26 (3%)	45 (4%)	0	22 (3%)
Collect from river/rain	11 (1%)	135 (4%)	8 (2%)	56 (4%)	0	4 (0%)	3 (9%)	75 (10%)
Toilet/ septic tank in home								
Yes	558 (45%)	590 (18%)	205 (45%)	300 (23%)	348 (46%)	348 (21%)	5 (14%)	26 (4%)
Latrine in yard								
Yes	577 (46%)	2456 (75%)	314 (68%)	1227 (93%)	228 (30%)	523 (43%)	35 (100%)	706 (98%)

*The sample of households in Eldoret, Kenya is smaller than the other two communities as random sampling was switched to purposeful sampling midway through data collection to ensure a higher sample of LPG households available for subsequent phases of the CLEAN-Air(Africa) study. Note: variables for some countries do not add up to total sample size due to missing data or elimination of variable categories for brevity.

Households Cooking with LPG

Over half (52%, n=1,458) of households cooking with LPG used it as a primary fuel; very few (4%, n=109) exclusively cooked with LPG and 44% (n=1,263) used LPG as a secondary fuel (Table 2). In Obuasi, two-

thirds of households reported using LPG as a primary fuel (67%; n=679), compared with one-third (37%; n=316) of households in Eldoret; in Mbalmayo LPG was used roughly equally as a primary and secondary fuel (48%; n=463). LPG was most frequently stacked with wood in Mbalmayo, and charcoal in Eldoret and Obuasi (Figure 2).

Figure 2. Most common primary, secondary (and tertiary) cooking fuel combinations by community. For brevity, only the most common fuel combinations (>35 households) were included. Among study households, there were nearly 200 different cooking fuel combinations.

Nearly half (47%) of households primarily cooking with LPG said it was not always available for purchase (Table 2); more than double those exclusively cooking with LPG (21%). LPG consumption varied substantially from 0.75-67.0 kg/capita/yr. Median LPG consumption was 14.4 kg/capita/yr [IQR:10.4,24.0] in Eldoret, Kenya, 20.0 kg/capita/yr [IQR:15.0,30.0] in Mbalmayo, Cameroon and 23.2 kg/capita/yr [IQR:14.5,36.0] in Obuasi, Ghana. Mean cost of cylinder refills was lowest among households exclusively cooking with LPG (\$0.99 USD/kg (SD:0.50)) and highest among households using LPG as a secondary fuel (\$1.27 USD/kg (SD:0.67)).

In Eldoret, 72% of participants cooking exclusively with LPG were 10 minutes or less from a retailer compared with 47% and 36% of households using LPG as a primary or secondary fuel, respectively. Having an LPG retail point within walking distance was six times more common among households using LPG exclusively (61%) than those using LPG as a secondary fuel (11%).

Table 2. LPG usage characteristics among households reporting exclusive, primary or secondary use of LPG (n=2,830)

	Overall (N=2,830)			Mbalmayo, Cameroon (N=958)		Obuasi, Ghana (N=1,020)			Eldoret, Kenya (N=852)		
	Exclusive (N=109)	Primary (N=1,458)	Secondary (N=1,263)	Primary (N=463)	Secondary (N=495)	Exclusive (N=77)	Primary (N=679)	Secondary (N=264)	Exclusive (N=32)	Primary (N=316)	Secondary (N=504)
Unavailability of fuel											
Always available	86 (79%)	779 (53%)	613 (49%)	193 (42%)	229 (46%)	55 (71%)	345 (51%)	174 (66%)	31 (97%)	241 (76%)	210 (42%)
<4 times/yr	12 (11%)	396 (27%)	321 (25%)	116 (25%)	129 (26%)	11 (14%)	225 (33%)	68 (26%)	1 (3%)	55 (17%)	124 (25%)
4-12 times/yr	8 (7%)	124 (9%)	170 (13%)	43 (9%)	54 (11%)	8 (10%)	64 (9%)	13 (5%)	0	17 (5%)	103 (20%)
>12 times/yr	3 (3%)	79 (5%)	102 (8%)	34 (7%)	32 (6%)	3 (4%)	42 (6%)	8 (3%)	0	3 (1%)	62 (12%)
Don't know	0	80 (5%)	57 (5%)	77 (17%)	51 (10%)	0	3 (0%)	1 (0%)	0	0	5 (1%)
Usage (# days previous wk)											
0	5 (5%)	66 (5%)	274 (22%)	24 (5%)	125 (25%)	5 (6%)	35 (5%)	39 (15%)	0	7 (2%)	110 (22%)
1-3	18 (17%)	105 (7%)	179 (14%)	30 (6%)	68 (14%)	17 (22%)	65 (10%)	44 (17%)	1 (3%)	10 (3%)	67 (13%)
4-6	8 (7%)	190 (13%)	148 (12%)	89 (19%)	68 (14%)	8 (10%)	89 (13%)	47 (18%)	0	12 (4%)	33 (7%)
7	78 (72%)	1079 (74%)	629 (50%)	304 (66%)	208 (42%)	47 (61%)	490 (72%)	134 (51%)	31 (97%)	285 (90%)	287 (57%)
Years cooking with LPG											
<1 yr	12 (11%)	112 (8%)	158 (13%)	14 (3%)	24 (5%)	3 (4%)	12 (2%)	8 (3%)	8 (25%)	31 (10%)	71 (14%)
1-2 yr	40 (37%)	437 (30%)	348 (28%)	51 (11%)	43 (9%)	4 (5%)	16 (2%)	10 (4%)	8 (25%)	45 (14%)	105 (21%)
2-5 yr	11 (10%)	57 (4%)	103 (8%)	85 (18%)	85 (17%)	18 (23%)	121 (18%)	64 (24%)	7 (22%)	100 (32%)	139 (28%)
5-10 yr	21 (19%)	529 (36%)	333 (26%)	93 (20%)	123 (25%)	32 (42%)	273 (40%)	107 (41%)	8 (25%)	71 (22%)	118 (23%)
>10 yr	25 (23%)	306 (21%)	288 (23%)	205 (44%)	194 (39%)	20 (26%)	257 (38%)	75 (28%)	1 (3%)	67 (21%)	64 (13%)
Cylinder size											
6 kg	56 (51%)	457 (31%)	439 (35%)	6 (1%)	7 (1%)	28 (36%)	212 (31%)	20 (8%)	28 (88%)	239 (76%)	412 (82%)
9 kg	4 (4%)	18 (1%)	9 (1%)	0	0	4 (5%)	18 (3%)	9 (3%)	0	0	0
12.5 kg	1 (1%)	464 (31%)	466 (37%)	442 (95%)	462 (93%)	1 (1%)	22 (3%)	4 (2%)	0	0	0
13 kg	4 (4%)	79 (6%)	71 (6%)	0	0	0	8 (1%)	0	4 (12%)	71 (22%)	71 (14%)
14.5 kg	42 (38%)	292 (20%)	60 (6%)	0	0	42 (52%)	404 (59%)	60 (30%)	0	0	0
Consumption (kg/capita/yr) (Median (IQR))*	29.0 [7.2, 18.8]	20.0 [13.6, 29.0]	12.0 [7.2, 18.8]	20.0 [15.0, 30.0]	12.5 [9.4, 20.0]	36.0 [23.2, 58.0]	23.2 [14.5, 36.0]	23.2 [12.0, 34.8]	24.0 [14.0, 36.0]	14.4 [10.4, 24.0]	9.0 [6.0, 14.4]
Refill cost per kg (USD) (Mean (SD))	0.99 (0.50)	1.05 (0.59)	1.27 (0.67)	1.03 (0.18)	1.03 (0.15)	0.77 (0.24)	0.85 (0.65)	1.20 (1.73)	1.52 (0.56)	1.56 (0.56)	1.52 (0.38)
Travel time to refill point (min)											
Home delivery	11 (10%)	103 (7%)	48 (4%)	0	0	11 (14%)	93 (14%)	43 (16%)	0	10 (3%)	5 (1%)

1-10	38 (35%)	390 (27%)	349 (28%)	133 (29%)	133 (27%)	15 (19%)	110 (16%)	37 (14%)	23 (72%)	147 (47%)	179 (36%)
11-20		437 (30%)	398 (32%)	171 (37%)	171 (35%)	14 (18%)	168 (25%)	60 (23%)	6 (19%)	98 (31%)	167 (33%)
	20 (18%)										
21-30	23 (21%)	349 (24%)	363 (29%)	114 (25%)	141 (28%)	20 (26%)	185 (27%)	87 (33%)	3 (9%)	50 (16%)	135 (27%)
30+	17 (16%)	162 (11%)	72 (6%)	30 (6%)	24 (5%)	17 (22%)	123 (18%)	37 (14%)	0	9 (3%)	11 (2%)
Transportation mode for refill											
Motorbike	12 (11%)	593 (41%)	804 (64%)	419 (90%)	452 (91%)	0	12 (2%)	3 (1%)	12 (38%)	162 (51%)	349 (69%)
Car	32 (29%)	363 (25%)	167 (13%)	15 (3%)	6 (1%)	32 (42%)	310 (46%)	104 (39%)	0	38 (12%)	57 (11%)
On foot	32 (29%)	210 (14%)	122 (10%)	12 (3%)	11 (2%)	12 (16%)	119 (18%)	56 (21%)	20 (62%)	79 (25%)	55 (11%)
Public transport	22 (20%)	172 (12%)	85 (7%)	2 (0%)	0	22 (29%)	145 (21%)	58 (22%)	0	25 (8%)	27 (5%)
Home delivery	11 (10%)	103 (7%)	48 (4%)	0	0	11 (14%)	93 (14%)	43 (16%)	0	10 (3%)	5 (1%)
Number of cylinders owned											
1	77 (71%)	976 (67%)	1001 (79%)	364 (79%)	403 (81%)	46 (60%)	366 (54%)	146 (55%)	31 (97%)	246 (78%)	452 (90%)
2	25 (23%)	353 (24%)	189 (15%)	71 (15%)	57 (12%)	24 (31%)	227 (33%)	93 (35%)	1 (3%)	55 (17%)	39 (8%)
3+	7 (6%)	111 (8%)	40 (3%)	12 (3%)	9 (2%)	7 (9%)	86 (13%)	25 (9%)	0	13 (4%)	6 (1%)
Number of stove burners											
1	58 (53%)	460 (32%)	536 (42%)	4 (1%)	10 (2%)	31 (40%)	242 (36%)	129 (49%)	27 (84%)	214 (68%)	397 (79%)
2	10 (9%)	339 (23%)	308 (24%)	218 (47%)	223 (45%)	8 (10%)	60 (9%)	24 (9%)	2 (6%)	61 (19%)	61 (12%)
3 or more	41 (38%)	641 (44%)	385 (30%)	226 (49%)	236 (48%)	38 (49%)	377 (56%)	111 (42%)	3 (9%)	38 (12%)	38 (8%)
Time since last stove purchase											
<2 years	43 (54%)	645 (56%)	502 (47%)	225 (57%)	183 (45%)	34 (72%)	321 (73%)	126 (75%)	9 (28%)	99 (32%)	193 (39%)
3-4 years	17 (22%)	244 (21%)	236 (22%)	114 (29%)	104 (26%)	4 (9%)	69 (16%)	20 (12%)	13 (41%)	61 (19%)	112 (23%)
5-6 years	10 (13%)	134 (12%)	163 (15%)	35 (9%)	72 (18%)	7 (15%)	46 (10%)	18 (11%)	3 (9%)	53 (17%)	73 (15%)
7+ years	9 (11%)	130 (11%)	167 (16%)	24 (6%)	46 (11%)	2 (4%)	5 (1%)	3 (2%)	7 (22%)	101 (32%)	118 (24%)

*Annual per capita consumption is a derived variable obtained by multiplying cylinder size (kg) by self-reported number of annual refills

The relationship between the proportion of households reporting LPG as a primary fuel and family size was modified by the number of LPG stove burners. Only 10% of primary LPG households with a large family size (≥ 7 members) used a single-burner stove, compared with 50% of the smallest households (1-2 members) (Figure 3). A monotonically increasing association existed between the proportion of

households primarily cooking with LPG and proportion using multi-burner stoves among households with more than four members.

Figure 3. Proportion of households cooking with LPG as a primary or secondary fuel by number of stove burners, stratified by number of family members

Modeling of LPG as a primary or secondary fuel choice

The final multivariable model modestly characterized (pseudo $R^2_{\text{marginal}}=0.42$; AUC=0.82) primary versus secondary use of LPG for cooking (Table S2). Demographics ($R^2_{\text{marginal}}=0.11$) and LPG supply-related factors ($R^2_{\text{marginal}}=0.10$) explained a higher proportion of model variability than SES ($R^2_{\text{marginal}}=0.03$) (Table S2). Households with 1-2 members had more than twice the predicted probability (89% (95%CI: 79,95)) of primarily using LPG than households with 7-8 family members (39% (95%CI: 24,56)) (Figure 4). Lower availability of LPG and higher refill costs were associated with a lower predicted probability of primary use of the fuel in a monotonically decreasing manner (Figure 4). Specifically, 76% (95%CI: 60,87) of households reporting a refill cost of <\$0.86 USD/kg were predicted to use LPG as a primary fuel, compared with 65% (95%CI: 51,78), 58% (95%CI: 42,72) and 45% (95%CI: 28,62), of households reporting a cylinder refill cost of \$0.86-1.00USD/kg, \$1.01-1.10USD/kg and >\$1.10USD/kg, respectively.

Figure 4. Average-adjusted predicted probabilities of using LPG as a primary versus secondary cooking fuel stratified by community. All probabilities account for quantitative covariates centered at their mean (all covariates listed in Table S4 in Supplement).

Modeling of Annual Per Capita LPG Consumption

Half ($R^2_{\text{marginal}}=0.49$; cross validation (CV) $R^2=0.39$) of the variability in LPG consumption was explained by covariates included in the final model (root mean square error (RMSE)=0.52 kg/capita/yr; CV RMSE=0.54 kg/capita/yr) (Table S3). Household demographics ($R^2_{\text{marginal}}=0.31$) explained significantly times more of this variability than household SES ($R^2_{\text{marginal}}=0.0$). Households with 3-4 members consumed an average of 16.4 kg/capita/yr (95%CI: 13.5,19.8), nearly 13 kg/capita/yr less than households of 1-2 individuals (29.1 kg/capita/yr (95%CI: 24.0,35.2)) (Table S5).

Households using a double-burner or triple-burner LPG stove consumed an average of 8.2 kg/capita/yr (95%CI: 6.4,10.3) and 6.1 kg/capita/yr (95%CI: 4.8,7.5), respectively, more LPG than households with single-burner stoves, irrespective of SES and family size (Figure 5). Households exclusively cooking with LPG consumed 2.4 kg/capita/yr (95%CI: 1.2,3.8) more than households that stacked LPG with another fuel (Table S5).

Figure 5. Average-adjusted annual per capita LPG consumption (kg), stratified by community. Per capita consumption is presented with covariates centered at their mean (all covariates listed in Table S5 in Supplement).

Participants that took 11-20 minutes, 21-30 minutes or >30 minutes to travel to LPG retailers consumed an average of 1.0 kg/capita/yr (95%CI: 0.0,1.9), 1.4 (95%CI: 0.5,2.3) and 1.6 kg/capita/yr (95%CI: 0.0,3.0) less than those who could reach an LPG retailer in under 11 minutes (Table S4). In addition, households reporting the lowest costs for refilling their LPG (<\$0.86USD/kg) consumed 1.4 (95%CI: 0.2,2.6), 2.3 (95%CI: 0.8,3.7) and 4.9 (95%CI: 3.2,6.5) kg/capita/yr more than participants reporting higher refill costs of \$0.86-1.00USD/kg, \$1.01-1.10USD/kg and >\$1.10USD/kg, respectively.

Households Exclusively Cooking with Polluting Fuels

Among households exclusively cooking with polluting fuels (n=2,685), nearly half (47%, n=1,248) reported having previously cooked with LPG (Table S6); the proportion varied nearly three-fold by community (Obuasi:63% (n=612), Mbalmayo:48% (n=399), Eldoret:24% (n=237)). Only 10% (n=272) of households cooking exclusively with polluting fuels indicated being satisfied with their current cooking fuel.

Inability to afford the upfront costs of purchasing LPG stoves/equipment was the dominant reason (70%; n=1,889) reported for not currently cooking with LPG (Figure 6). High refill costs were cited as a barrier for LPG use by twice as many households previously cooking with LPG (37%) as those that had not (19%) (Table S6). Concerns over LPG safety were reported by 18% (n=470) of households not currently using LPG; this concern was highest among households in Obuasi (30%; n=292); the proportion was twice as high as in Mbalmayo (14%; n=117) and five times higher than in Eldoret (6%; n=61).

Figure 6. Reasons for not cooking with LPG among households exclusively cooking with polluting fuels (N=2,685)

Discussion

By quantitatively modeling the impact of SES, fuel cost and accessibility on LPG usage, this multinational study demonstrates that supply-related issues, including inconsistent fuel supply and higher cylinder refill and transportation costs are critical barriers to uptake and sustained use of LPG in peri-urban communities in SSA. Households indicating a consistent supply of LPG at retailers had over 20% higher predicted probability of using LPG as a primary fuel than those reporting inconsistent supply, irrespective of household SES (Table S4). Households reporting the lowest refill costs also had a 30% higher probability of using LPG as a primary fuel (Figure 4) and consumed 6.67 kg/capita/yr (95%CI: 5.16,8.60) more than households reporting the highest refill costs (Figure 5). High refill costs were commonly reported by households cooking exclusively with polluting fuels, particularly in Obuasi (50%) and Mbalmayo (40%), possibly indicative that customers using typically smaller cylinders in Kenya (6 kg) compared with those used in Cameroon and Ghana (>12 kg) may be less sensitive to changes in the refill price.

A negative dose-response relationship between higher LPG consumption and lower transportation cost and shorter time to obtain an LPG refill (Figure 5) matches with previous cooking fuel choice research conducted in rural communities in Ghana.³¹⁻³³ Thus, policies that improve proliferation of last-mile

distributors (i.e. refilling stations) in peri-urban communities, which would decrease the collective population's travel time and associated costs, will likely pay dividends in terms of increasing population-level LPG usage. Other LPG supply chain enhancements, including increasing bulk storage and filling facilities, are important for expanding access²³ and have been identified as a priority by Cameroonian government.¹³

Consumer finance mechanisms, including unconditional cash transfers,³⁴ microfinance and pay-as-you-go LPG,³⁵ which involve direct cylinder home deliveries, can help offset the financial burden associated with transport and cost of refills. PAYG LPG has shown promise in urban settings,³⁶ but will be more logistically challenging to implement in peri-urban areas due to higher transportation costs and enhanced distribution networks needed to ensure timely home deliveries.¹³

The Pradhan Mantri Ujjwala Yojana (PMUY) programme achieved rapid expansion of LPG access but did not lead to higher usage among rural Indian households.^{24,37} A study among 8,000 PMUY program beneficiaries proposed that long travel times from rural Indian villages to refill points was a likely driver of 30% lower LPG consumption.²⁵ While this study proposed that fuel access is important at a village-level, we find that accessibility may play a role at smaller scales in an African context; a 10-minute longer travel time to a retailer within a community may be a deterrent to LPG usage (Figure 5). Indeed, a low intraclass correlation coefficient (0.01) in the consumption model emphasizes that LPG consumption was predominantly influenced at a household-level (Table S3). These results contribute to growing evidence that accessibility/affordability of refills are critical bottlenecks that should be priority targets for policymakers to expand LPG use.

Socioeconomic Status and Demographics

Younger households and smaller families were more likely to primarily use LPG and had higher consumption rates (Figure 5), similar to findings from a study of PMUY beneficiaries in India.²⁵ Moreover, using multi-burner LPG stoves greatly increased the probability of households with 5 members or greater primarily using LPG (Figure 3), likely because multi-burner stoves offer greater time and fuel savings to larger families. Using a double-burner stove was associated with substantially higher LPG consumption (21.92 kg/capita/yr (95%CI: 17.84,26.93)) compared with use of a single-burner stove (14.09 kg/capita/yr (95%CI: 11.53,17.21)). The ability to cook two meals simultaneously on double-burner stoves was an advantage of LPG over kerosene reported by households in Nairobi, with users associating the double-burner stove with greater time and fuel savings.³⁶ Participants in another Kenyan study stated having “no need to stack” when using double-burner stoves.³⁸ Thus, increasing access to multi-burner LPG stoves seems a simple, yet potentially highly effective intervention to increase clean cooking.

In contrast to India,²⁴ years cooking with LPG was not significantly associated with consumption (Table S5), potentially highlighting the importance of LPG fuel costs remaining price competitive in the long term to prevent reversion to polluting cooking fuels. This finding is further supported by households previously cooking with LPG being more likely than households with no prior LPG experience to cite high

cylinder refill costs as a reason for not cooking with LPG (Table S6). Additionally, the strongly negative association of family size with consumption and use as a primary fuel suggests that LPG usage is also dependent on its ability to prepare sizeable meals in a reasonable amount of time,³⁹ which may be more difficult for larger families.

Household income was not significantly associated with use of LPG as a primary fuel (Table S4), demonstrating that usage does not necessarily intensify in a linear manner with increasing SES, but may follow a complicated trajectory due to various supply-related and contextual factors.^{40,41}

LPG consumption statistics

Self-reported frequency of stove usage during the past week was an insignificant predictor of annual LPG consumption, possibly due to seasonal income fluctuations reported by 65% of households (Table 2), which can lead to large within-household variation in consumption patterns.³⁷ However, fuel stacking was associated with 17% lower LPG consumption (2.3 kg/capita/year reduction).

Estimated median annual per capita consumption in Mbalmayo, Eldoret and Obuasi were relatively similar (40% higher, 13% higher, 8% lower, respectively) to national rates reported in the Global LPG Partnership National Feasibility Studies in 2017 (14.2 kg/capita/yr in Cameroon, 12.8 kg/capita/yr in Kenya and 25.0 kg/capita/yr in Ghana).⁴²⁻⁴⁴ It is unclear if the differences result from population-level changes in consumption from 2017-2019 or bias in self-reporting of consumption (Table S7), which has occurred in previous studies.⁴⁵ Nonetheless, the self-reported consumption rates are about half that of households in more developed countries (e.g. Brazil, Indonesia, Peru) with more established LPG supply chains.¹⁴

Safety Concerns

LPG safety concerns were prevalent among households cooking with polluting fuels, particularly in Obuasi (30%) (Figure 6). A higher proportion in Obuasi compared with the other communities is likely attributed to the 'customer-controlled cylinder model' currently implemented in Ghana, which places customers in charge of cylinder maintenance, contributing to more frequent, serious LPG accidents.⁴² The Ghana 'Sustainable Energy 4 All' plan called for a national switch to the 'branded cylinder recirculation model', which ensures proper refilling practices and correct disposal of cylinders, as LPG marketers are responsible for cylinder maintenance and safety.⁴⁶

Households Using Polluting Fuels

There was high aspiration to use clean cooking fuels among those cooking exclusively with polluting fuels (Figure 6). While high fuel costs were the dominant reason for not using LPG, overcoming the affordability barrier will not lead to universal use in these communities due to safety concerns and an inconsistent supply. Nearly half (47%) of participants currently not cooking with LPG have cooked with LPG previously. While unable to ascertain if households that formerly cooked with LPG used it as their

primary fuel and whether they have completely stopped using it or routinely switch between fuels (e.g. due to periodic income fluctuations), it is evident that LPG refill costs play a key role in discontinuing use of LPG (Figure 6).⁴⁷ Reversion to polluting cooking fuels has been reported in longitudinal studies,⁴⁸ with a prevalence as high as 35% (China).⁴⁹

Strengths and Limitations

This study is one of the largest modeling studies of determinants of LPG consumption in SSA. While calculation of self-reported annual LPG consumption via two different survey questions showed disagreement (Figure S1), sensitivity analyses revealed that this discrepancy did not significantly impact study findings (Table S8). As the direction of misclassification between the self-reported LPG consumption variables was the same among all households (consumption using self-reported number of annual refills was always higher than that calculated via average cylinder lifetime), we expect that misclassification was non-differential and therefore biased toward a null finding. We recommend that future studies collecting self-reported data on LPG consumption phrase survey questions in terms of 'average cylinder lifetime' rather (or in addition to) number of annual cylinder refills to protect against overreporting. As other studies have found low agreeableness between self-reported and objective measures,⁴⁵ we further recommend that absolute measures of LPG consumption reported in this study be interpreted with caution.

This study examined household energy decisions in a unique, peri-urban context. As the extent of fuel stacking and availability of free biomass typically varies between rural and peri-urban households,^{27,33} and research has shown differences in LPG consumption in urban, rural and peri-urban settings,⁴²⁻⁴⁴ the study results may not hold outside of peri-urban communities.

Conclusions

This study presents robust empirical evidence of the critical role of supply-side determinants and access to multi-burner stoves in increasing LPG consumption among peri-urban households in SSA. Supply-related factors may play a considerable role in LPG consumption even at small scales (e.g. 10-minute travel intervals) within a community. Energy policies targeting the LPG supply chain, including expanding distribution/retailing networks can help accelerate growth of the clean cooking market in Sub-Saharan Africa, leading to positive environmental and health impacts.

Methods

The *Global Health Research Group on Clean Energy Access for the prevention of Non-communicable disease in Africa through clean Air (CLEAN-Air(Africa))* program consists of applied research and capacity building within SSA.⁵⁰ This study reports on findings from the first phase of CLEAN-Air(Africa), involving randomly administered surveys in three peri-urban communities: Mbalmayo, Cameroon; Obuasi, Ghana and Eldoret, Kenya. Mbalmayo is an agricultural town in central Cameroon with 60,000 residents that is

an hour drive away from Yaoundé, the country's capital. Obuasi is a gold-mining community in southern Ashanti, Ghana with a population of almost 200,000 that is an hour drive away from Kumasi (capital city of the Ashanti region). Eldoret is a town surrounded by agricultural land, located at an elevation of over 2000 meters in Western Kenya and has a population of nearly 500,000; it is currently the fastest growing town in Kenya according to the 2019 National Census.

In each community, 2,000 households were surveyed to ensure a sufficient sampling frame for comparative research between households cooking primarily with LPG and exclusively with polluting fuels in later phases of CLEAN-Air(Africa). The surveys included detailed questions on cooking behaviours, including WHO Harmonized survey questions on fuel use (<https://www.who.int/airpollution/household/survey-harmonization/en/>). Completion took approximately 20 minutes. Due to a switch from random to stratified sampling (by primary cooking fuel type) midway through data collection in Eldoret (in order to ensure a sufficient sample of households using LPG for future phases of CLEAN-Air(Africa)), population-based results are reported among a subset of 757 households for this location.

Surveys were administered to the main cook of the household using secure smartphone technology (Mobenzi Researcher in Cameroon/Kenya; Research Electronic Data Capture (REDCap) in Ghana) from April-August 2019. Mobenzi is a secure data collection software system (data encrypted at source) whereby data from predefined surveys are collected by smartphone application and automatically uploaded via the phone's SIM card and synced to the Mobenzi cloud (or when the phone is connected to a wireless network if there is no mobile signal).⁵¹ REDCap is an encrypted web application for creating and managing online surveys and databases; data are wirelessly imported directly to the database servers.

Two multilevel (households nested within communities) models were built: (1) use of LPG as a primary or secondary cooking fuel (logistic regression) and (2) self-reported quantity (kilograms) of LPG consumed per capita (log-linear regression). Results from logistic regression modeling are depicted as the average-adjusted predicted probability of using LPG as a primary cooking fuel. Findings from log-linear regression, are portrayed as the average-adjusted annual LPG per capita consumption (kilograms/capita/year).

Model 1: LPG cooking fuel (primary/secondary)_{ik} = $\beta_0 + \beta_1 + b_i + e_{ik}$ (logistic regression)

Model 2: $\ln(\text{kg LPG/capita/year})_{ik} = \beta_0 + \beta_1 + b_i + e_{ik}$ (log-linear regression)

In Model 1, *LPG cooking fuel (primary/secondary)_{ik}* represents whether the *k*th participant in community *i* uses LPG as a primary or secondary cooking fuel. In Model 2, *$\ln(\text{kg LPG/capita/year})_{ik}$* represents the natural log transformed annual per capita consumption of *k*th participant in community *i*. In both models, β_0 is the overall intercept, β_1 represents fixed effects, *b_i* is the community-level random effect and ε_{ik} is the residual error.

Annual per capita consumption of LPG was estimated in two ways: (1) multiplying self-reported cylinder size by number of annual refills and dividing by the number of household members and (2) dividing 12 months by the self-reported average duration (months) of a cylinder refill to obtain a second estimate of self-reported number of annual refills and multiplying that by cylinder size then dividing by the number of household members. Sensitivity analyses examined the effects of using both metrics on the modeling results. The distribution of annual per capita LPG consumption (kg) was right-skewed so data was log-transformed before modeling. Principal components analysis (PCA) was run on owned assets to generate an alternative measure of household SES.⁵² (add Vyas citation). The first principal component was grouped into quartiles and tested as a predictor in both regression models.

Model fit was assessed via a combination of the coefficient of determination (R^2), Akaike information criterion (AIC) and 10-fold cross validation (training and test datasets split at the community level to ensure more accurate evaluation of model performance), with consideration given to selection of parsimonious models. The cross-validated R^2 is reported for the linear model⁵³ and the area under the Receiver Operating Characteristic curve (AUC) is reported for the logistic model.⁵⁴ All data analysis was conducted in R (version 3.5.1).⁵⁵ Ethical approval was obtained from the University of Liverpool, United Kingdom and local Institutional Review Boards in each study country. Informed consent was obtained from all participants prior to conducting the study.

Declarations

Acknowledgements

The authors would like to sincerely express gratitude to the field staff in each of the three study communities for their dedication and efficient effort in administering thousands of household surveys in a timely manner. This research was funded by the National Institute for Health Research (NIHR) (ref: 17/63/155) using UK aid from the UK government to support global health research.

Author Contributions

MS assisted with survey design, supervised data collection, managed, cleaned and analyzed all data, and wrote the first and final drafts of the paper. EP and DP designed and supervised the conduct of the CLEAN-Air(Africa) study and supervised the interpretation of the data. EN assisted with data cleaning, management and interpretation. MB, EB, JM, ES, TT and JS led data collection and study logistics in their respective study countries. DM, BM KPA and RQ designed and supervised the conduct of the CLEAN-Air(Africa) study, directed study implementation and supervised data collection in their respective countries. RAdC helped oversee data management in the CLEAN-Air(Africa) study. All co-authors reviewed and commented on the final manuscript.

Conflicts of Interest

The authors have no conflicts of interest to declare.

References

1. Health Effects Institute. State of Global Air 2020. 2020;28.
2. Bruce N, Pope D, Rehfuess E, Balakrishnan K, Adair-Rohani H, Dora C. WHO indoor air quality guidelines on household fuel combustion: Strategy implications of new evidence on interventions and exposure-risk functions. *Atmos Environ*. 2015 Apr;106:451–7.
3. Po JY, FitzGerald JM, Carlsten C. Respiratory disease associated with solid biomass fuel exposure in rural women and children: systematic review and meta-analysis. *Thorax*. 2011;66(3):232–9.
4. Li L, Yang A, He X, Liu J, Ma Y, Niu J, et al. Indoor air pollution from solid fuels and hypertension: A systematic review and meta-analysis. *Environmental Pollution*. 2020 Apr 1;259:113914.
5. Yu K, Qiu G, Chan K-H, Lam K-BH, Kurmi OP, Bennett DA, et al. Association of Solid Fuel Use With Risk of Cardiovascular and All-Cause Mortality in Rural China. *JAMA*. 2018 Apr 3;319(13):1351–61.
6. Sumpter C, Chandramohan D. Systematic review and meta-analysis of the associations between indoor air pollution and tuberculosis. *Tropical Medicine & International Health*. 2013 Jan;18(1):101–8.
7. Bailis R, Drigo R, Ghilardi A, Masera O. The carbon footprint of traditional woodfuels. *Nature Clim Change*. 2015 Mar;5(3):266–72.
8. Bond TC, Sun H. Can Reducing Black Carbon Emissions Counteract Global Warming? *Environ Sci Technol*. 2005 Aug 1;39(16):5921–6.
9. Kumar P, Mehta S. Poverty, gender, and empowerment in sustained adoption of cleaner cooking systems: Making the case for refined measurement. *Energy Research & Social Science*. 2016 Sep 1;19:48–52.
10. WHO | Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children [Internet]. WHO. [cited 2016 Jul 10]. Available from: <http://www.who.int/indoorair/publications/burning-opportunities/en/>
11. International Energy Agency. World Energy Outlook 2020 [Internet]. Paris, France: IEA; 2020 p. 12. Available from: <https://www.iea.org/reports/world-energy-outlook-2020>
12. Bruce NG, Aunan K, Rehfuess EA. Liquefied Petroleum Gas as a Clean Cooking Fuel for Developing Countries: Implications for Climate, Forests, and Affordability.:44.
13. Bruce N, de Cuevas RA, Cooper J, Enonchong B, Ronzi S, Puzzolo E, et al. The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation. *Energy for Sustainable Development*. 2018 Oct;46:103–10.
14. Van Leeuwen V, Evans A, Hyseni B. Increasing the use of liquefied petroleum gas in cooking in developing countries [Internet]. LiveWire: The World Bank; 2017 Jan [cited 2020 May 25] p. 1–8. Report No.: 114846. Available from: <http://documents.worldbank.org/curated/en/707321494347176314/Increasing-the-use-of-liquefied-petroleum-gas-in-cooking-in-developing-countries>

15. Shen G, Hays MD, Smith KR, Williams C, Faircloth JW, Jetter JJ. Evaluating the Performance of Household Liquefied Petroleum Gas Cookstoves. *Environmental Science & Technology*. 2018 Jan 16;52(2):904–15.
16. Shupler M, Hystad P, Birch A, Miller-Lionberg D, Jeronimo M, Arku RE, et al. Household and personal air pollution exposure measurements from 120 communities in eight countries: results from the PURE-AIR study. *The Lancet Planetary Health*. 2020 Oct 1;4(10):e451–62.
17. Simkovich SM, Williams KN, Pollard S, Dowdy D, Sinharoy S, Clasen TF, et al. A Systematic Review to Evaluate the Association between Clean Cooking Technologies and Time Use in Low- and Middle-Income Countries. *International Journal of Environmental Research and Public Health*. 2019 Jun 27;16(13):2277.
18. Heltberg R. Fuel switching: evidence from eight developing countries. *Energy Economics*. 2004 Sep;26(5):869–87.
19. Leach G. The energy transition. *Energy Policy*. 1992 Feb 1;20(2):116–23.
20. Masera OR, Saatkamp BD, Kammen DM. From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development*. 2000 Dec;28(12):2083–103.
21. Puzzolo E, Pope D, Stanistreet D, Rehfuess EA, Bruce NG. Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use. *Environmental Research*. 2016 Apr;146:218–34.
22. Lewis JJ, Pattanayak SK. Who adopts improved fuels and cookstoves? A systematic review. *Environmental health perspectives*. 2012;120(5):637–45.
23. Puzzolo E, Zerriffi H, Carter E, Clemens H, Stokes H, Jagger P, et al. Supply Considerations for Scaling Up Clean Cooking Fuels for Household Energy in Low- and Middle-Income Countries. *GeoHealth*. 2019;3(12):370–90.
24. Mani S, Jain A, Tripathi S, Gould CF. The drivers of sustained use of liquified petroleum gas in India. *Nat Energy* [Internet]. 2020 Apr 27 [cited 2020 May 28]; Available from: <http://www.nature.com/articles/s41560-020-0596-7>
25. Gould CF, Hou X, Richmond J, Sharma A, Urpelainen J. Jointly modeling the adoption and use of clean cooking fuels in rural India. *Environ Res Commun*. 2020 Aug;2(8):085004.
26. Pope D, Bruce N, Higgerson J, Hyseni L, Stanistreet D, MBatchou B, et al. Household Determinants of Liquefied Petroleum Gas (LPG) as a Cooking Fuel in SW Cameroon. *EcoHealth* [Internet]. 2018 Oct 1 [cited 2018 Nov 27]; Available from: <http://link.springer.com/10.1007/s10393-018-1367-9>
27. Stanistreet D, Hyseni L, Puzzolo E, Higgerson J, Ronzi S, Anderson de Cuevas R, et al. Barriers and Facilitators to the Adoption and Sustained Use of Cleaner Fuels in Southwest Cameroon: Situating ‘Lay’ Knowledge within Evidence-Based Policy and Practice. *IJERPH*. 2019 Nov 26;16(23):4702.
28. Choumert-Nkolo J, Combes Motel P, Le Roux L. Stacking up the ladder: A panel data analysis of Tanzanian household energy choices. *World Development*. 2019 Mar 1;115:222–35.

29. Alem Y, Beyene AD, Köhlin G, Mekonnen A. Modeling household cooking fuel choice: A panel multinomial logit approach. *Energy Economics*. 2016 Sep;59:129–37.
30. Johnson MA, Chiang RA. Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets. *Environmental Health Perspectives* [Internet]. 2015 Mar 27 [cited 2015 Apr 21]; Available from: <http://ehp.niehs.nih.gov/1408681>
31. Asante KP, Afari-Asiedu S, Abdulai MA, Dalaba MA, Carrión D, Dickinson KL, et al. Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*. 2018 Oct;46:94–102.
32. Rahut DB, Behera B, Ali A. Factors determining household use of clean and renewable energy sources for lighting in Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews*. 2017 May 1;72:661–72.
33. Wiedinmyer C, Dickinson K, Piedrahita R, Kanyomse E, Coffey E, Hannigan M, et al. Rural–urban differences in cooking practices and exposures in Northern Ghana. *Environ Res Lett*. 2017 Jun;12(6):065009.
34. Aung T, Bailis R, Chilongo T, Ghilardi A, Jumbe C, Jagger P. Energy access and the ultra-poor: Do unconditional social cash transfers close the energy access gap in Malawi? *Energy for Sustainable Development*. 2021 Feb 1;60:102–12.
35. Puzzolo E, Cloke J, Parikh J, Evans A, Pope D. National Scaling Up of LPG to achieve SDG 7: Implications for Policy, Implementation, Public Health and Environment. [Internet]. p. 16. Available from: https://www.mecs.org.uk/wp-content/uploads/2020/2002/MECS-LPG-Briefing-Paper_Jan-2020.pdf
36. Shupler M, O'Keefe M, Puzzolo E, Nix E, Cuevas RA de, Mwitari J, et al. Pay-as-you-go LPG supports sustainable clean cooking in Kenyan informal urban settlement, including during a period of COVID-19 lockdown. *medRxiv*. 2020 Nov 23;2020.11.20.20235978.
37. Kar A, Pachauri S, Bailis R, Zerriffi H. Using sales data to assess cooking gas adoption and the impact of India's Ujjwala programme in rural Karnataka. *Nature Energy* [Internet]. 2019 Jul 15 [cited 2019 Aug 6]; Available from: <http://www.nature.com/articles/s41560-019-0429-8>
38. Ochieng CA, Zhang Y, Nyabwa JK, Otieno DI, Spillane C. Household perspectives on cookstove and fuel stacking: A qualitative study in urban and rural Kenya. *Energy for Sustainable Development*. 2020 Dec 1;59:151–9.
39. Nuño Martínez N, Mäusezahl D, Hartinger SM. A cultural perspective on cooking patterns, energy transfer programmes and determinants of liquefied petroleum gas use in the Andean Peru. *Energy for Sustainable Development*. 2020 Aug 1;57:160–7.
40. Bisaga I, Parikh P. To climb or not to climb? Investigating energy use behaviour among Solar Home System adopters through energy ladder and social practice lens. *Energy Research & Social Science*. 2018 Oct 1;44:293–303.
41. Neto-Bradley AP, Choudhary R, Bazaz A. Slipping through the net: Can data science approaches help target clean cooking policy interventions? *Energy Policy*. 2020 Sep 1;144:111650.

42. GLPGP. National Feasibility Assessment: LPG for Clean Cooking in Ghana. New York: The Global LPG Partnership; 2018.
43. GLPGP. National Feasibility Study: LPG for Clean Cooking in Kenya. New York: The Global LPG Partnership.; 2018.
44. GLPGP. National Feasibility Assessment: LPG for Clean Cooking in Cameroon. New York: The Global LPG Partnership; 2019.
45. Kar A, Brauer M, Bailis R, Zerriffi H. The risk of survey bias in self-reports vs. actual consumption of clean cooking fuels. *World Development Perspectives*. 2020 Jun 1;18:100199.
46. Clean Cooking Alliance. Scaling LPG For Cooking in Developing Markets: Insights from Tanzania [Internet]. Washington (DC); 2019 Sep [cited 2020 Jun 14]. Available from: <https://www.enea-consulting.com/en/scaling-lpg-for-cooking-in-developing-markets/>
47. Carrión D, Prah R, Gould CF, Agbokey F, Mujtaba M, Pillarisetti A, et al. Using longitudinal survey and sensor data to understand the social and ecological determinants of clean fuels use and discontinuance in rural Ghana. *Environ Res Commun*. 2020 Oct;2(9):095003.
48. Shupler M, Hystad P, Gustafson P, Rangarajan S, Mushtaha M, Jayachtria KG, et al. Household, community, sub-national and country-level predictors of primary cooking fuel switching in nine countries from the PURE study. *Environmental Research Letters*. 2019 Jul 29;14(8):085006.
49. Carter E, Yan L, Fu Y, Robinson B, Kelly F, Elliott P, et al. Household transitions to clean energy in a multiprovincial cohort study in China. *Nature Sustainability*. 2020 Jan;3(1):42–50.
50. Puzzolo E, Menya D, Asante KP, MBatchou B, Quansah R, Anderson de Cuevas R, et al. Clean Energy Access for the Prevention of Non-Communicable Disease in Africa: the NIHR CLEAN-Air (Africa) Global Health Research Group. *Environmental Epidemiology*. 2019 Oct;3:319.
51. van Heerden A, Norris S, Tollman S, Richter L, Rotheram-Borus MJ. Collecting maternal health information from HIV-positive pregnant women using mobile phone-assisted face-to-face interviews in Southern Africa. *J Med Internet Res*. 2013 Jun 10;15(6):e116.
52. Vyas S, Kumaranayake L. Constructing socio-economic status indices: how to use principal components analysis. *Health Policy Plan*. 2006 Nov;21(6):459–68.
53. Yuchi W, Gombojav E, Boldbaatar B, Galsuren J, Enkhmaa S, Beejin B, et al. Evaluation of random forest regression and multiple linear regression for predicting indoor fine particulate matter concentrations in a highly polluted city. *Environ Pollut*. 2019 Feb;245:746–53.
54. Maroco J, Silva D, Rodrigues A, Guerreiro M, Santana I, de Mendonça A. Data mining methods in the prediction of Dementia: A real-data comparison of the accuracy, sensitivity and specificity of linear discriminant analysis, logistic regression, neural networks, support vector machines, classification trees and random forests. *BMC Research Notes*. 2011 Aug 17;4(1):299.
55. R Core Team. R: A language and environment for statistical computing. [Internet]. Vienna, Austria: R Foundation for Statistical Computing; 2017. Available from: <http://www.R-project.org/>

Figures

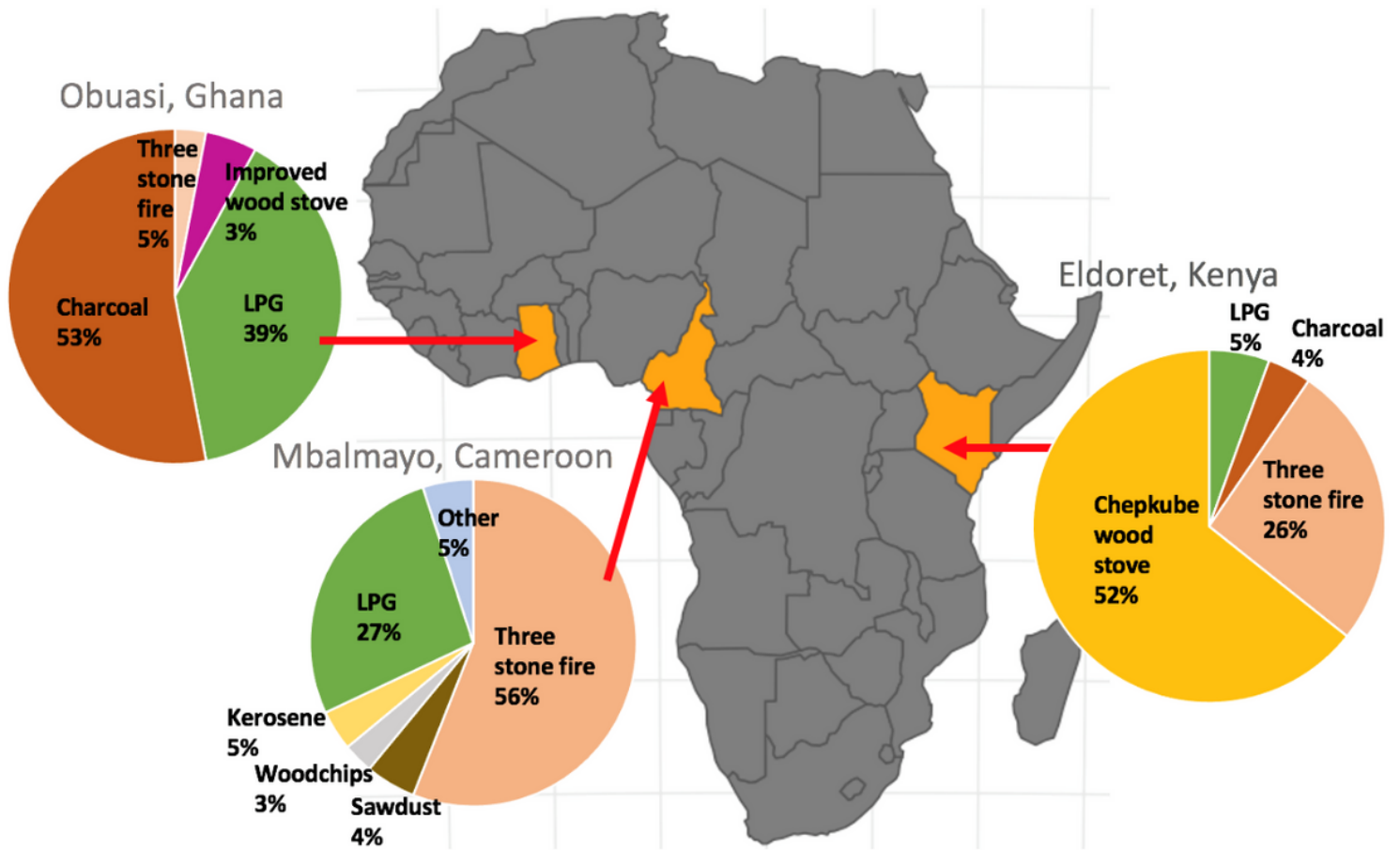


Figure 1

Primary cooking fuel types among three peri-urban communities in Ghana, Cameroon and Kenya

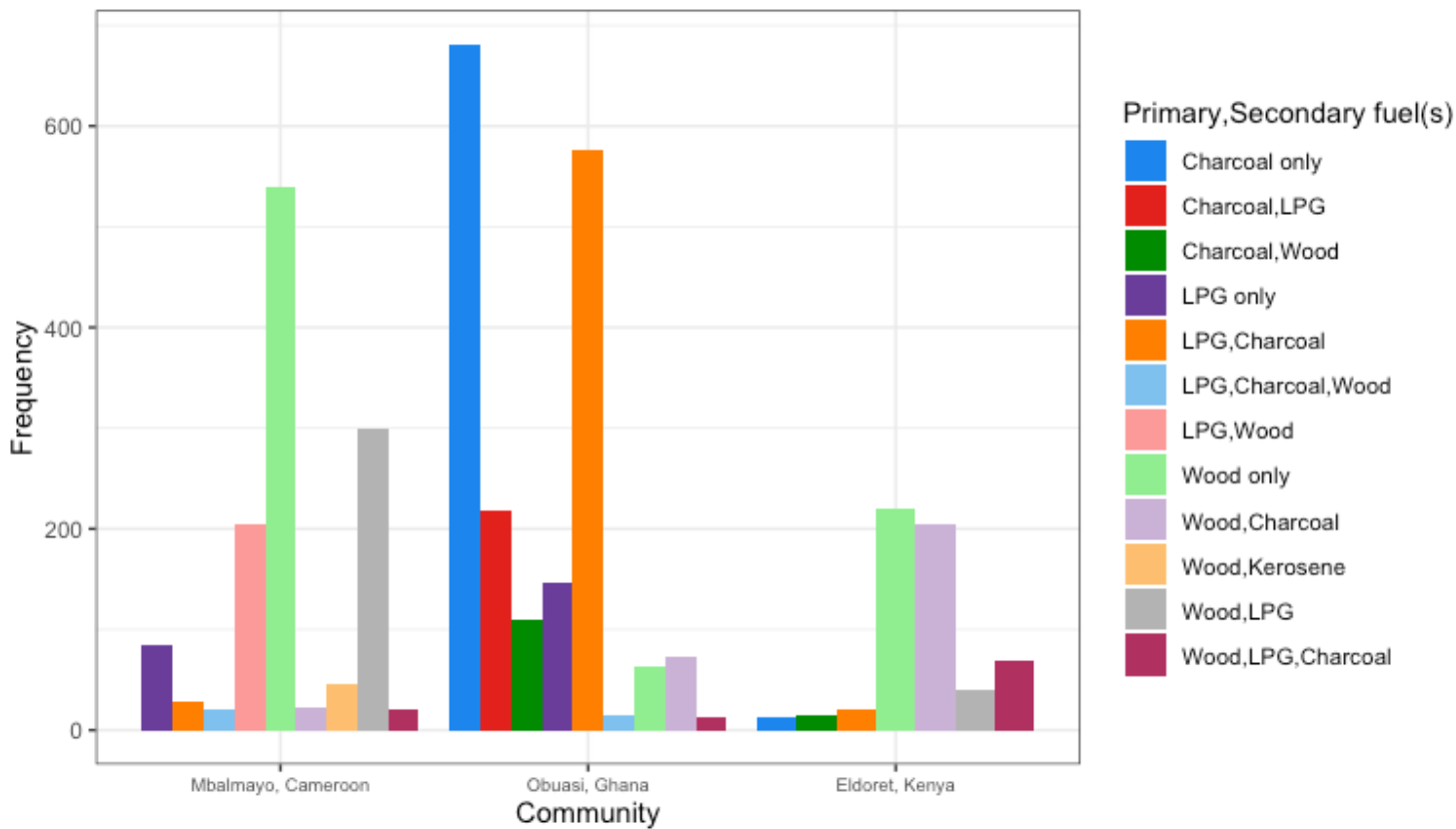


Figure 2

Most common primary, secondary (and tertiary) cooking fuel combinations by community. For brevity, only the most common fuel combinations (>35 households) were included. Among study households, there were nearly 200 different cooking fuel combinations.

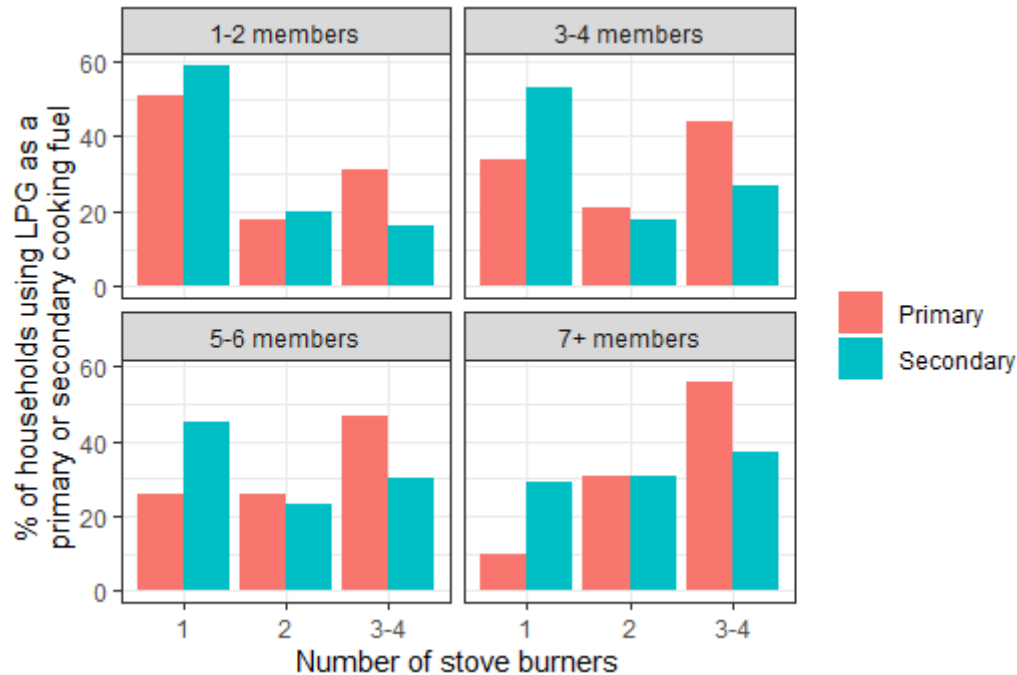


Figure 3

Proportion of households cooking with LPG as a primary or secondary fuel by number of stove burners, stratified by number of family members

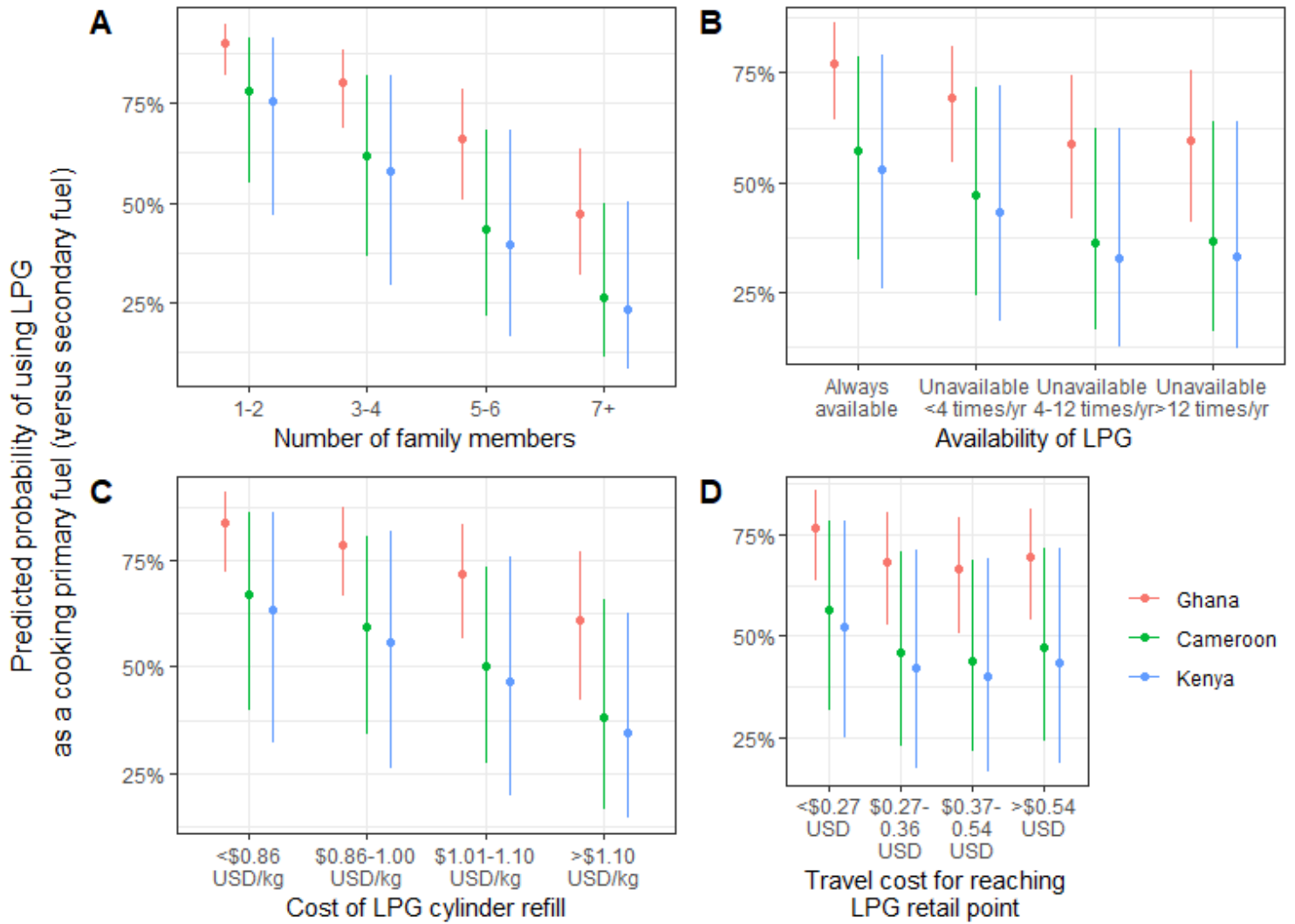


Figure 4

Average-adjusted predicted probabilities of using LPG as a primary versus secondary cooking fuel stratified by community. All probabilities account for quantitative covariates centered at their mean (all covariates listed in Table S4 in Supplement).

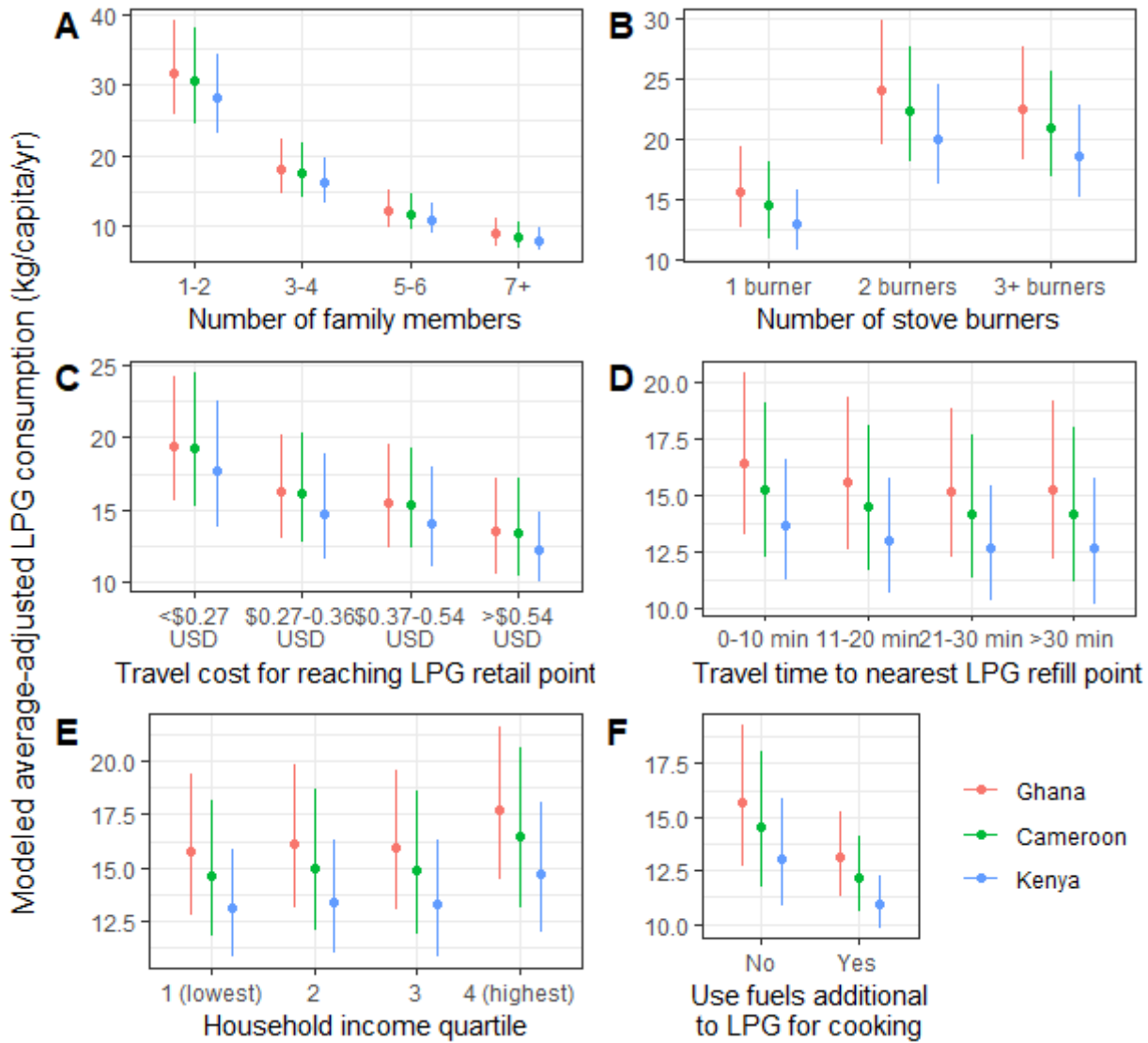


Figure 5

Average-adjusted annual per capita LPG consumption (kg), stratified by community. Per capita consumption is presented with covariates centered at their mean (all covariates listed in Table S5 in Supplement).

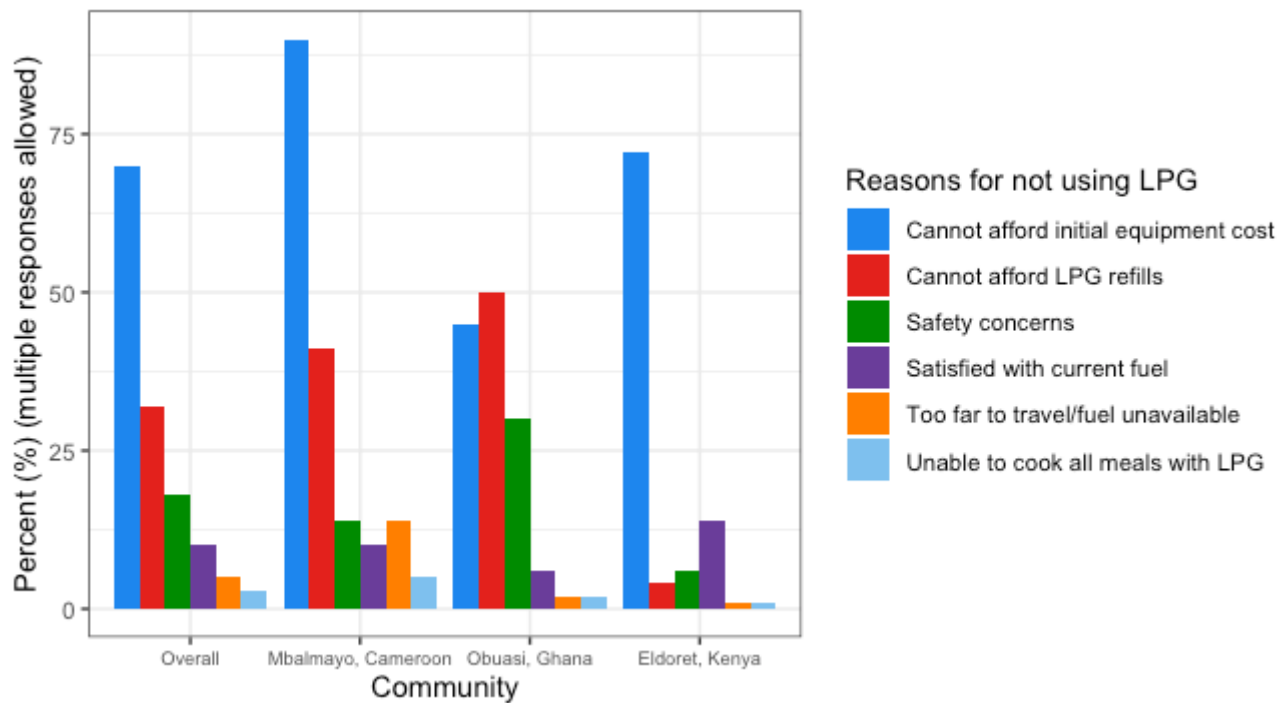


Figure 6

Reasons for not cooking with LPG among households exclusively cooking with polluting fuels (N=2,685)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementalInformationv9RapidSurvey.docx](#)