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Published in: Solar Energy
DOI: 10.1016/j.solener.2020.11.077

Available online: 26 Dec 2020

Citation:
Yadav, P., Davies, P. J. & Sarkodie, S. A. (2021). Fuel choice and tradition: Why fuel stacking and the energy ladder are out of step? Solar Energy, 214, 491-501. doi: 10.1016/j.solener.2020.11.077

Fuel choice and tradition: Why fuel stacking and the energy ladder are out of step?

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Abstract

Multiple fuel use, incorporated within the concept of fuel stacking is prevalent in households at the beginning and mid-way in their ascension up the energy ladder. However, households cannot fully let go of their traditional energy sources presenting inherent policy complexities and contradictions within energy transition theories. Empirical insights into the determinants of clean energy transitions are presented that highlight the need to recognise both fuel switching and stacking occurs in many rural households. It focuses on rural communities in India and illuminates policy dilemmas. The study reveals that fuel stacking is likely to remain a key part of the socio-cultural energy tradition that will impact progress towards low carbon and a cleaner energy transition. We therefore argue targeted policy interventions, multi-stakeholder collaboration and strong energy governance is needed to incorporate socio-cultural traditions

particularly linked to cooking. This suggests new energy policy that must offer flexibility in order to achieve the twin goals of universal energy access and decarbonising energy systems.

Keywords: Energy ladder; Fuel choices; Energy poverty; Fuel stacking; India

1. Introduction

Energy remains the main driver of economic development and is one that binds many households and communities disadvantaged through the energy-poverty nexus (Jain 2011);(IEA 2017);(Reddy 2015). Traditional and conventional energy production and consumption have resulted in resource depletion and environmental pollution (Batinge et al. 2019);(Singh et al. 2016). Concurrently, energy poverty constitutes one of the dimensional notions of both economic and social poverty (Ray et al. 2016). Combined, these factors constitute social, environmental and economic injustice at multiple scales. Despite substantive technical improvements to energy reform in the last decade, the scale of global energy poverty is alarming. About three billion people remain reliant on traditional cooking fuel and about one billion people lack access to electricity (United Nations Statistics Division 2018). The majority of this energy-deprived population resides in rural parts of low and middle-income countries constituting more than half of the population in these regions. Inefficient cooking and high dependence on kerosene for lighting is the root cause of negative health, social and environmental outcomes (Baquié and Urpelainen 2017);(UNDP 2012). In particular, women and children in these communities are most affected as they often spend more time on fuel collection and suffer disproportionally from the indoor pollution (Chakraborty and Mondal 2018);(Dutta et al. 2012);(Pachauri et al. 2004).

A growing consensus to curb carbon emissions and improve household health have led international and national sustainable development agendas to facilitate a transition to a comprehensive clean energy profile at the household level (Khandker et al. 2012). While clean energy offers avenues to advance economic, environmental and social outcomes (Rosenthal et al. 2018), there remain inequities as to its availability and access (Sovacool et al. 2017). When new forms of energy is provided, there are positive educational outcomes, gender improvements (Smith and Sagar 2014), income-generating prospects (Chakravorty et al. 2014) and advancing overall living standards of rural communities (Cabraal et al. 2005);(Heltberg 2004). Therefore, energy is an intertwined to socio-economic and an environmental concern (United Nations Statistics Division 2018). From a policy perspective, energy provision and transitions are subject to and captured by many factors and interests that determine the decisions of government, industry and households (Muller and Yan 2018).

This study reports empirical findings on the determinants of fuel choices, access to electricity and fuel switching in rural households with different levels of energy access. In addition, electricity aspirations in rural households via current and future appliance use are examined as a surrogate for future demand and how this may influence energy ladder and fuel stacking assumptions. A case study approach from parts of rural India is used for this research that explores three research questions:

1. What energy fuel trends are dominant in rural residential energy use?
2. How do the pattern of fuel stacking, electricity use, appliance ownership and appliance aspiration among rural households change across various household energy types?
3. What are the socio-economic factors that determine access to electricity, household fuel (lighting and cooking) choice and or energy stacking?

The findings support policy formation through empirical evidence-based household data. The results also offer additional insight to address both energy-poverty nexus and to reduce indoor pollution. The novelty of this research lies in showing how household fuel choices are made and how decisions challenge theoretical understandings of fuel stacking and the energy ladder drawing on household data rather than aggregated datasets. We first discuss the outline, followed by methods in section 2, section 3 presents the empirical analysis and discussion, and section 4 provides conclusions.

1.1. Fuel choice: Conceptual framework

From a research perspective, there are two major hypotheses offering insight into fuel choice and are used extensively in the literature: energy ladder and fuel stacking. The nature and topology of fuel transitions within both positions are critical as they shape personal decisions and behaviours and public welfare, hence present as a priority socio-economic and environmental issue for policymakers.

1.1.1. Energy ladder

Many studies in developing countries offer insights into household energy needs and energy switching. Traditionally, the 'energy ladder model' has been widely utilised as a theoretical and analytical framework to study the dynamics of fuel switching (Leach 1992). The energy ladder model posits a linear and upward movement from old fuels to new fuels. According to the energy ladder model, fuel switching occurs as a three-step process (Fig.1), largely driven by income and relative fuel costs (Barnes et al. 2004);(Saatkampa et al. 2000). At the household level, research applying the energy ladder has shown that multiple fuels are used, characterised by the simultaneous use of modern and traditional fuels (Heltberg 2004);(Heltberg 2005);(Masera et al. 2000). Consequently, the energy ladder notions that a single fuel is used and then replaced by an upward movement to a more efficient new fuel. This theory is not without its critics (Masera et al. 2000);(Rahut et al. 2017).

1.1.2. Fuel stacking

The notion of multiple fuel use or use of a combination of fuels is termed fuel stacking. Households use fuels based on their needs, budgets and preferences (Dewees 1989);(Heltberg 2004);(Masera et al. 2000);(Pachauri and Spreng 2003). Fuel stacking suggests a household will only partly switch to a different fuel or that they will accumulate and continue to use multiple fuels. In effect, households will rely on traditional fuels for certain activities in addition to adopting modern fuels. Fuel stacking occurs due to three major factors: high cost of modern energy sources; cultural preferences, including familiarity with existing fuel; and to avoid total dependence on one fuel that may be a manifestation of price and supply vulnerability (Alem et al. 2016);(Leach 1992);(Masera et al. 2000). Studies into fuel stacking also report household energy transition does not follow a ladder-like progression, rather rural households continue to rely on traditional fuels to meet the majority of their energy needs with modern fuels supplementing demand if and where accessible. Therefore, in rural areas within so-called ‘emerging countries’, there is a practice of using a portfolio of fuels.

Underlying the concept of fuel stacking are various decision-making processes that lead a household to both switch and use multiple fuels. This is a complex process and driven by multiple factors (Kowsari and Zerriffi 2011). Empirical studies have demonstrated fuel switching in rural households is a function of income, education, household size, fuel availability, location and other social and regional demographic factors (Chan et al. 2017);(Farsi et al. 2007);(Heltberg 2004);(Heltberg 2005);(Narasimha Rao and Reddy 2007);(Pachauri et al. 2004);(Wu et al. 2017). Notably, households of varying socio-economic status are likely to make different choices (Pachauri et al. 2004). Therefore, an analysis of the energy choices of households must consider the impact of different incomes and how this applies across different locations.

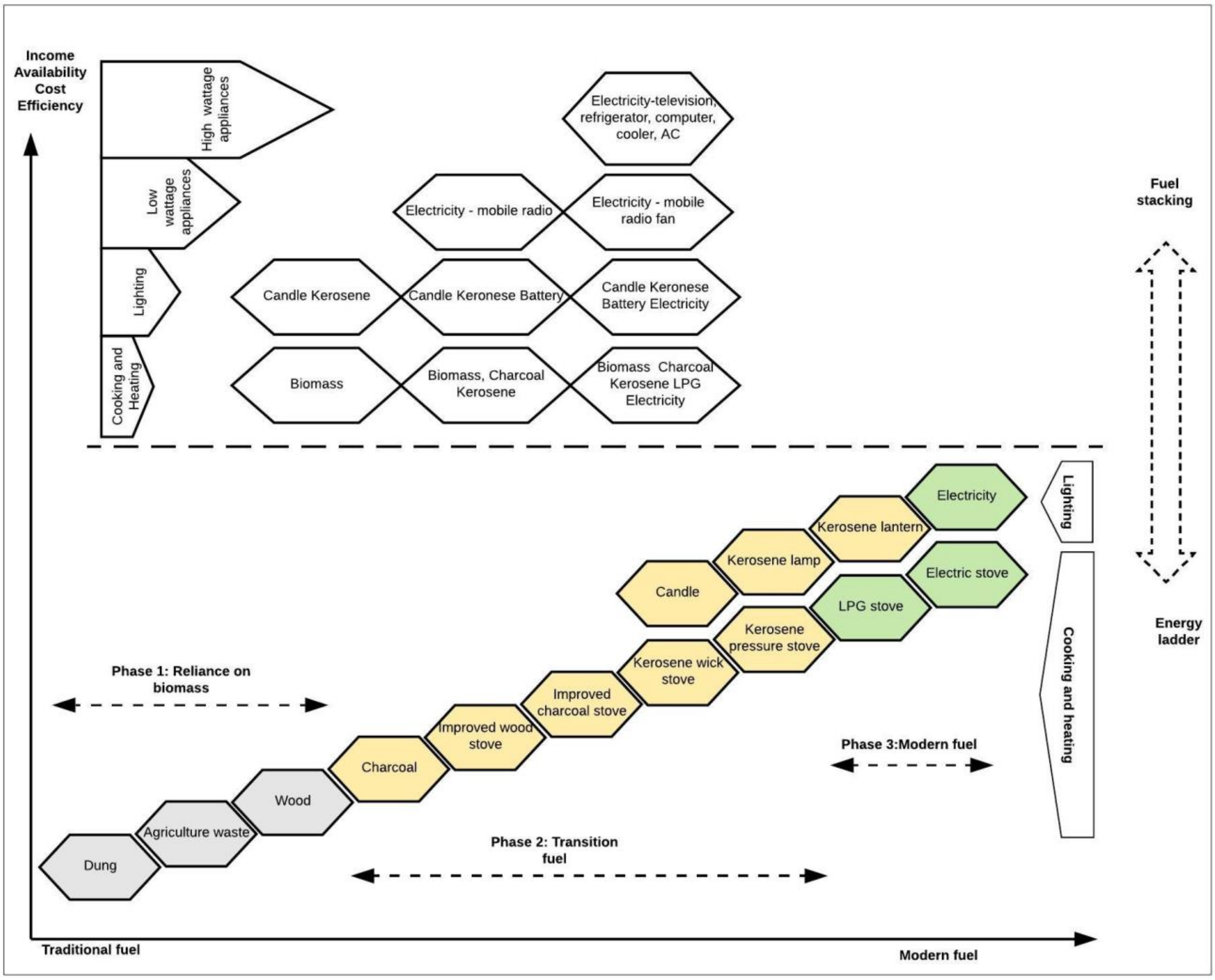


Fig.1: Swing between traditional and modern fuel use with rural households representing both exclusive fuel switching (bottom) and fuel stacking (top). Source: Authors' compilation based on (Leach 1992);(Masera et al. 2000).

1.2. Fuel stacking trends in India

Fuel use and fuel stacking in India is complex. It is driven by fuel availability, prices, household size and income and other demographic and regional variables (Narasimha Rao and Reddy 2007). Within households in rural India, fuel stacking exists (Cheng and Urpelainen 2014) notwithstanding national and state policy intentions that purport to assume energy transition based on the energy ladder. Below poverty line households, in particular, continue to rely on traditional fuels due to their lower price and availability when compared to modern fuels, despite detrimental health and pollution outcomes (Pachauri et al. 2004);(Rahut et al. 2017). A section of the below poverty line population when provided with highly subsidised modern fuel by the government often revert to use of traditional fuels during and following the end of subsidised energy programs. This points to the need to more deeply investigate how income and other factors impact on energy transitions and specifically how this relates to fuel stacking (Masera et al. 2000) and how social, economic and environmental policy outcomes can be achieved through energy transitions (Muller and Yan 2018) in such rural communities in India, notwithstanding the complexities contradictions of policy and household decision making.

1.3.Rural electrification and energy aspirations in India

Under broader climate and energy SDG agendas, increasing social and economic development in rural India can be best achieved through the provision of clean fuels to households (Parikh et al. 2012). Within the household, the convenience of electricity has achieved a better quality of life outcomes through the uptake of basic electrical goods (e.g. lighting and fans), increased access to infotainment sources (e.g. television), advancing the use of other electronics (e.g. refrigerators, computer and cloth iron) (Malakar 2018). In the case of India, these improvements have occurred in spite of the suboptimal grid electricity supply to rural communities that is subject to the frequent outage and voltage fluctuations (Khandker et al. 2014).

To sustain social and economic outcomes, there is a need to align energy demand, including energy aspirations, with a reliable supply using cleaner fuels (Parikh et al. 2012) that is also accessible and affordable (Reddy and Srinivas 2009). Therefore, investigating what determines fuel choice, we also explore current and aspirational appliance use in order to examine the role of energy and how this relates to the energy ladder and fuel stacking. In this study, we assume aspiration for appliance use represents the gap between the supply and demand in reliable and accessible electricity thus serving as a substitution or proxy for future electricity provision.

1.4. Indoor air and environmental pollution in India

The use of biomass and kerosene in rural households in developing countries, including India, are key sources of indoor air pollution (Sharma and Jain 2019). Household air pollution from solid fuel affects over 55% of the Indian population and causes high mortality and disease burden (Balakrishnan et al. 2019);(Rohra and Taneja 2016). Indoor air pollution disproportionally impacts the health of women (Chakraborty and Mondal 2018);(Deepthi et al. 2019) and is considered a major threat to household wellbeing (IEA 2017). The environmental stress of indoor air pollution can be related to the environmental Kuznets curve (EKC) hypothesis in that biomass fuels will have an immediate effect on resource availability and through its combustion contributes to pollution. The initial stages of economic development is characterised by environmental pressures, both in resources depletion and waste generation, leading to environmental pollution (Panayotou 1993); (Sarkodie and Strezov 2019 b). However, pollution experiences a decline at a turning point of income level according to the EKC hypothesis and presumably can be linked to the access and availability of cleaner fuels. This represents the theoretical point where decarbonisation of the economy may occur, which suggests a vertical climb in the energy ladder, and is inclusive of energy efficiency. According to the IPCC report (IPCC 2011), energy is the major contributor to global anthropogenic greenhouse emissions due to its role in economic development. Hence, developing a conceptual approach that examines the nexus between the energy ladder and fuel switching is valuable at a household to global level given population pressures, current and forecast energy demands, and global warming.

2. Materials and methods

We used data from 731 household surveys to analyse residential energy consumption collected from seven districts (Hardoi - 87 surveys, Jhansi - 163, Kannauj -78, Mathura - 120, Pratapgarh - 74, Sitapur - 118 and Sultanpur - 91) located in the northern State of Uttar Pradesh, India. Surveys were undertaken between April 2016 and June 2016. The interviews were conducted in person at the participants' house.

Villages were randomly selected based on available secondary information about the location of any solar projects in the district, as this offered an additional energy choice to households beyond grid-based electricity supply. Research Ethics Committee approval was obtained prior to conducting the interview with households. The final list of selected villages included those with solar services and surrounding villages without solar services was further discussed with the state utility officials to ensure the accuracy of village location in the district. Upon arrival on survey location, either village head or state utility local official/contractor/local member of public (or a combination these) known to have good knowledge of the village was contacted to help in connecting with the households for the interview.

The questionnaire (Appendix A) was originally designed in English then translated to Hindi (official and commonly understood the language in the state). The purpose of the study was explained to participants in Hindi and informed consent was signed before starting the interview. Participation in the survey was voluntary and participants were free to opt-out before, during and after the interview. The household surveys questionnaire had a mix of question types including simple, closed, and multiple responses and open questions to support both quantitative and qualitative analysis. The conversational interviewing technique was a deliberate strategy to ensure a higher understanding of the questions thus response accuracy. This reflected past literature reporting a low understanding of solar energy systems in rural areas (Friebe et al. 2013);(Urpelainen and Yoon 2015). The qualitative data was transformed into numerical data to utilise dataset for statistical analysis (Stata 2017).

The survey was conducted at the time of launch of 'Pradhan Mantri Ujjwala Yojana'[1] scheme on 1 May 2016. This central government initiative aimed to distribute 50 million subsidised LPG connections to women from Below Poverty Line (BPL) households. Therefore, the sample in this study represents LPG users before the launch of this scheme and none of the participants was beneficiaries of this program.

Participating households were classified into four types (Table 1). The classifications related to their current level of access to electricity. This classification was used to undertake analysis with respect to energy use, appliance ownership and rural aspiration to use modern energy.

For data analysis, we performed a pivot table to analyse, summarise and graphically present data on fuel choices and appliance use. The generalized linear model (glm) was employed for the regression analysis to present the role of socioeconomic factors in determining households' fuel (lighting and cooking) choices. The advantage of using the glm is to control for error distribution in the dependent variables without exhibiting a normal distribution. The glm fits generalized linear models and it can fit models by using either Iterated-Reweighted Least Squares (maximum quasi-likelihood) or Newton-Raphson (maximum likelihood)

[1] For more information, visit http://www.pmujjwalayojana.com/

optimization, which is the default. The glm of y with covariates x can be expressed as (McCullagh and Nelder 1989):

$$g\{E(y)\} = x\beta, y \sim F \quad (1)$$

where g ( ) is the link function and F denotes the distributional family.

Table 1: Types of household energy access

Household type	Description	No. of households
G^-O^-	Households without grid-connected electricity and no solar connection	176
G^+O^-	Household with only grid-connected electricity	351
G^-O^+	Households with only solar connected electricity	110
G^+O^+	Household with both grid and solar connected electricity	94
		Total 731

3. Results and discussion

3.1. Descriptive statistics

Table 2 provides descriptive statistics of variables (socio-economic and type of fuel use) from household data as used in the empirical analysis. Overall, it reveals the patriarchal nature of societies in rural India. These communities are mostly near or below poverty line income group and mainly work as farmers and/or labourers. Biomass, kerosene and grid electricity are key energy source used for cooking and lighting.

Table 2: Descriptive statistics - households

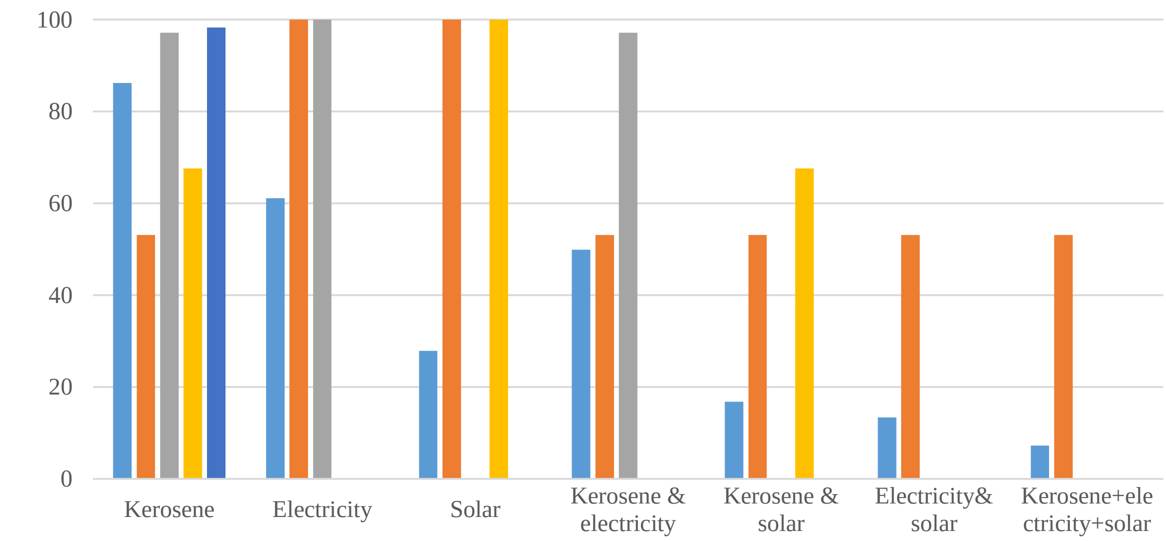
Variables	Frequency	Percentage
Household socio-economic characteristics (N=731)		
Participant's Gender *(Majority of survey participants were male due to the patriarchal social system in the study areas)*		
Male	656	90
Female	75	10
Participant's Age		
18 to 24	39	6
25 to 44	420	57
45 to 64	244	33
65 to 79	28	4
Education		
0 to class 5	387	53
Up to class 8	114	15
Up to class 12	161	22
Bachelor’s degree or above	69	10
Household size		
1 to 3	23	3
4 to 6	430	59
7 to 9	226	31
10 and more	52	7
Household monthly income *(converted to U.S. dollar where 1 $US = 69.52 INR as per the exchange rate on 5 January 2019)*		
13 – 475 (Below poverty line)	498	68
475 – 790	111	15
790 – 1250	62	9
1250 – 2150	31	4
2150 or above	25	3.5
Participant's occupation		

Employed or self – employed	94	13
Farmer and/or seasonal employment	428	59
Daily wager/Casual worker	143	19
Retired/homemakers/students	66	9
Household members studying		
None	96	13
1-2	497	68
3-4	128	18
5 and above	10	1
Fuel use variables *(Note: Fuel use is inclusive of stacking)*		
Biomass	698	95.5
Kerosene	630	86
Electricity	445	61
Solar	204	28
LPG	162	22

3.2. Fuel stacking patterns in surveyed households

The fuel stacking patterns in the sampled households are presented in Fig. 2. Most households, including electricity users, used some degree of biomass and kerosene for cooking and lighting respectively. Our study reports that grid-based electricity does not replace the use of kerosene, as would be assumed under the energy ladder. This can be attributed to two compounding factors, ongoing subsidies for kerosene (policy contradiction) and the poor reliability of grid-based electricity (performance issue). This is consistent with that of previous studies (Alem et al. 2016);(Leach 1992);(Masera et al. 2000). Individually and combined, these factors will continue to undermine a shift to clean fuel choices (CLEAN 2018):(Global Subsidies Initiative 2018) and national energy policy reforms.

A notable finding of the data was that only 17 % of solar users consumed kerosene, compared to 50 % for those with grid-based electricity. This may suggest solar systems while having their own limitations, have greater utility in progressing energy substitution. The promotion and use of household solar systems as an energy choice may better align to energy ladder, particularly where grid-based supply remains compromised by poor reliability.



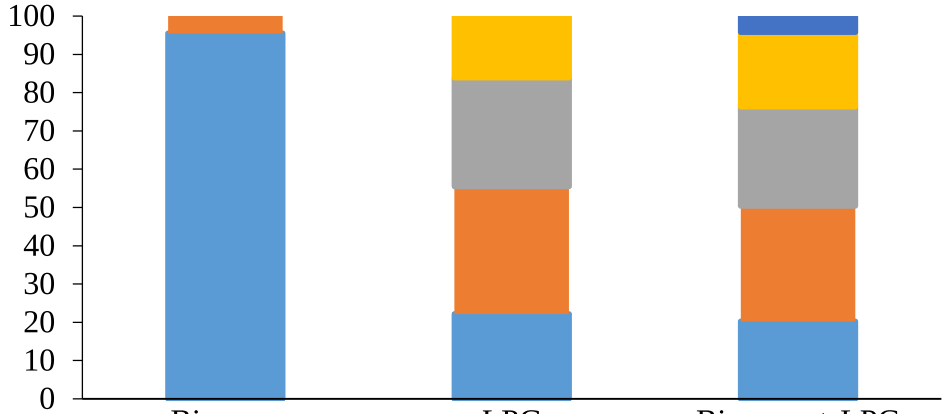
	Kerosene	Electricity	Solar	Kerosene & electricity	Kerosene & solar	Electricity& solar	Kerosene+ele ctricity+solar
All	86	61	28	50	17	13	7
G+O+	53	100	100	53	53	53	53
G+O-	97	100	0	97	0	0	0
G-O+	68	0	100	0	68	0	0
G-O-	98	0	0	0	0	0	0

Fig 2: Lighting fuel stacking in sample households (in %).

Fuel stacking for the purpose of cooking is shown in Figure 3. The results reported less than 3% of the surveyed households used coal and or charcoal. Consequently, these fuel types were excluded from the analysis of cooking fuel stacking. Biomass was reported as an important fuel source for cooking. This is attributed to its availability (Ravindra et al. 2019) and is of particular importance to the 59 % (Table 2) of households in this research associated with farming-based activities. Anecdotal responses from the survey also reported many households preferred to biomass (dung and firewood) for cooking on mud stoves as they favoured the taste of food cooked this way, a socio-cultural driver. One of such participants stated: *"Although I have LPG, I find some dishes e.g. chooni roti (a type of stuffed bread), bharta (made by chargrilled vegetables, especially eggplant) taste much better when cooked on mud stove)".* Notably, fuel stacking for cooking is present irrespective of a household's connection to agricultural activities or household income. This can partially explain why the energy ladder theory does not apply when examined through the lens of cooking in rural communities.

Overall households reported a low use of LPG (22 %) for cooking. This was attributed to its high cost and limited availability in rural areas, consistent with the findings of Gould and Urpelainen (Gould and Urpelainen 2018). Expectedly, the use of LPG in households (high income) with both grid and solar supply was 33 %, higher than any other subgroups (Fig.3) i.e. households using either grid electricity or solar power. Income affected the use of LPG within low-income households that were less able to afford cleaner fuels including LPG. This is likely to influence the national government Pradhan Mantri Ujjwala[2] program launched after the household survey as a means to improve access and lessen the cost of LPG and concurrently reduce indoor air pollution. It is anticipated that this program would change the cooking fuel stacking data noting that both ladder and stacking trends maintain a cultural profile of including biomass.

[2] Provided LPG to 50 million low-income households by August 2018 and extended the target to reach 80 million households with a total budget of $US 1·8 billion. Source: http://www.pmujjwalayojana.com/



	Biomass	LPG	Biomass + LPG
G-O-	97	5	4
G-O+	94	19	19
G+O-	96	28	26
G+O+	94	33	30
All	95	22	20

Fig 3: Cooking fuel stacking in sample households (in %).

3.3.Generalized linear model estimation of factors influencing households' fuel choice

The results of a regression analysis of household data affecting fuel choice is presented in Table 3. It summarises the estimated coefficient, standard error and p-value significance for key factors influencing household fuel choices obtained from generalized linear model. The regression models are within the 95 % confidence intervals. The results confirm household income as the main driver for switching to clean fuel (electricity, solar and LPG). Other factors contributing to switching to cleaner fuels include higher educational status of the family head and the type of employment where this occurs outside the agricultural sector. Employment outside the agricultural sector is likely to lower but not replace the availability, thus use of biomass, notwithstanding a cultural preference for biomass for cooking. To reduce this economic and cultural preference for reliance on biomass as a cooking fuel, various strategies would be required including targeted education programs and incentives or subsidies to shift the use of biomass from fuel to organic fertilizers (Martinot et al. 2001).

One of our research questions was to examine the relationship of education including the number of members of a household that were studying and whether this would affect the choice of fuels and support procurement of cleaner fuels (both grid and/or solar electricity). This was not observed. Rather, the size of the family was of greater influence for the use of off-grid solar. Larger families had a greater preference to use off-grid solar PV. This was despite the installed units being generally of low wattage, therefore, offering limited benefits to the family. A reason for the greater uptake in off-grid solar PV in larger families may be attributed to the following factors: First, the need of minimum level of power for lighting and mobile charging for night time and lighting is used within shared areas of the house such as kitchen and common sitting area. Second, it may reflect many households were from below the poverty line with bigger families that received their PV system from one of a number of government subsidy programs thus reporting higher levels of satisfaction compared to their pre-PV situation.

Table 3: Estimates of the generalized linear model explaining factors influencing household fuel choices

Variables	Lighting fuel			Cooking fuel	
	Kerosene	Electricity	Solar	Biomass	LPG
Household size	-0.0114	-0.0070	0.0848*	0.0090	-0.0119
	[0.0218]	[0.0298]	[0.0251]	[0.0125]	[0.0221]
Household annual income	-0.0039	0. 1111*	-0.0615*	-0.0420*	0.1567*
	[0.0146]	[0.0199]	[0.0168]	[0.0084]	[0.0148]

Education	-0.0155	0.0665*	-0.0022	0.01177	0.0909*
	[0.0143]	[0.0195]	[0.0164]	[0.0082]	[0.0145]
Members studying in the household	-0.0084	-0.0247	-0.0259	0.01002	0.0195
	[0.0243]	[0.0331]	[0.0278]	[0.0140]	[0.0245]
Occupation	-0.0133	0.0059	-0.0036	-0.01867**	-0.0104
	[0.0164]	[0.0224]	[0.0189]	[0.0095]	[0.0166]

*, ** denote significance at 1% and 5% level respectively; [ ] represents the standard error of the coefficient.

3.4. Quality of grid electricity supply, appliance use and aspirations of rural households

Households with access to grid electricity (G^+O^-, 351 and G^+O^+, 94) reported an overall benefit to the household. This was consistent with the findings of Banerjee et al. and Khandker et al. (Banerjee et al. 2015);(Khandker et al. 2014). In terms of user experience, households with access to grid electricity reported various levels of satisfaction with health and social benefits. However, satisfaction (not satisfied and not too satisfied) related to enabling increased working hours was the lowest (Fig. 5 (a) and 5 (b)). This was attributed to insufficient power supply (Fig. 6) during the evening and night hours. Grid electricity users stated that this energy source did not achieve its full benefits (e.g. to ease in household chores - especially in the kitchen and study time for children) due to peak hour power cuts. Quality of power services in rural areas is key to promote the use of modern electricity and subsequently deliver intended benefits to these communities. It should be noted, however, the benefits of the national government’s 24x7 power supply policy and grid-based electricity rollout are yet to be realised despite the notable grid extension that has occurred over the past 5 years (Gill et al. 2019).

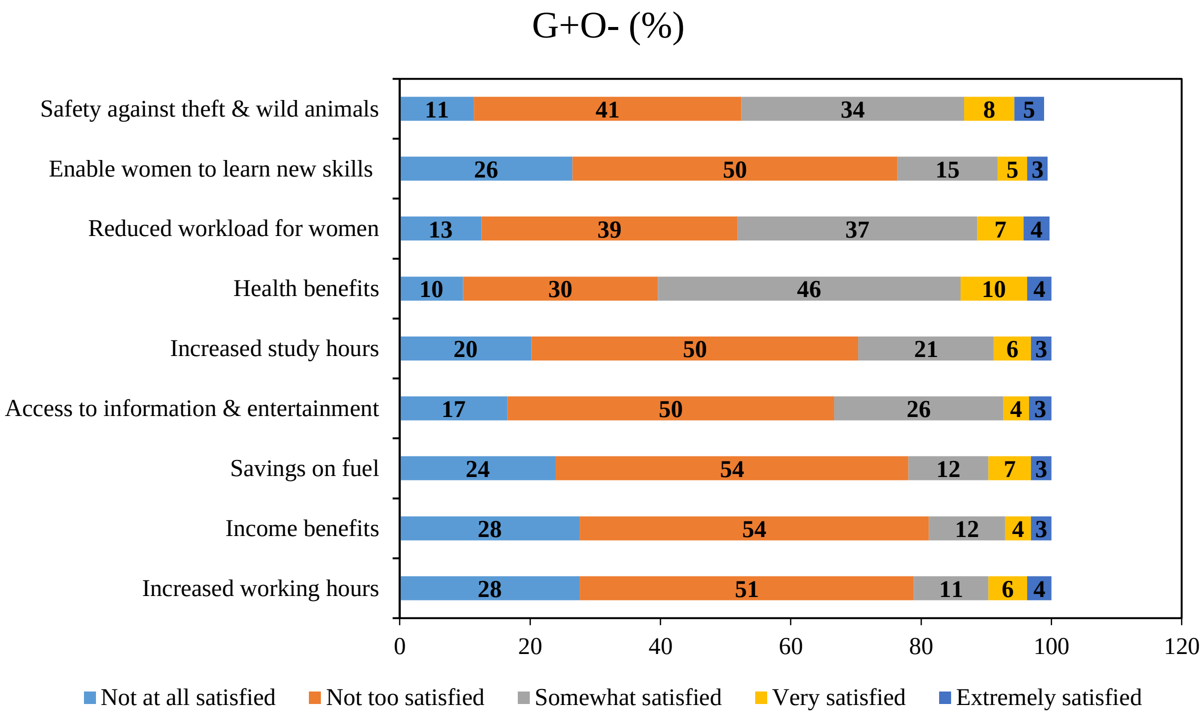


Fig. 5 (a): Satisfaction level with grid electricity among household using grid only.
(Note: Health benefits refer to improved indoor air quality)

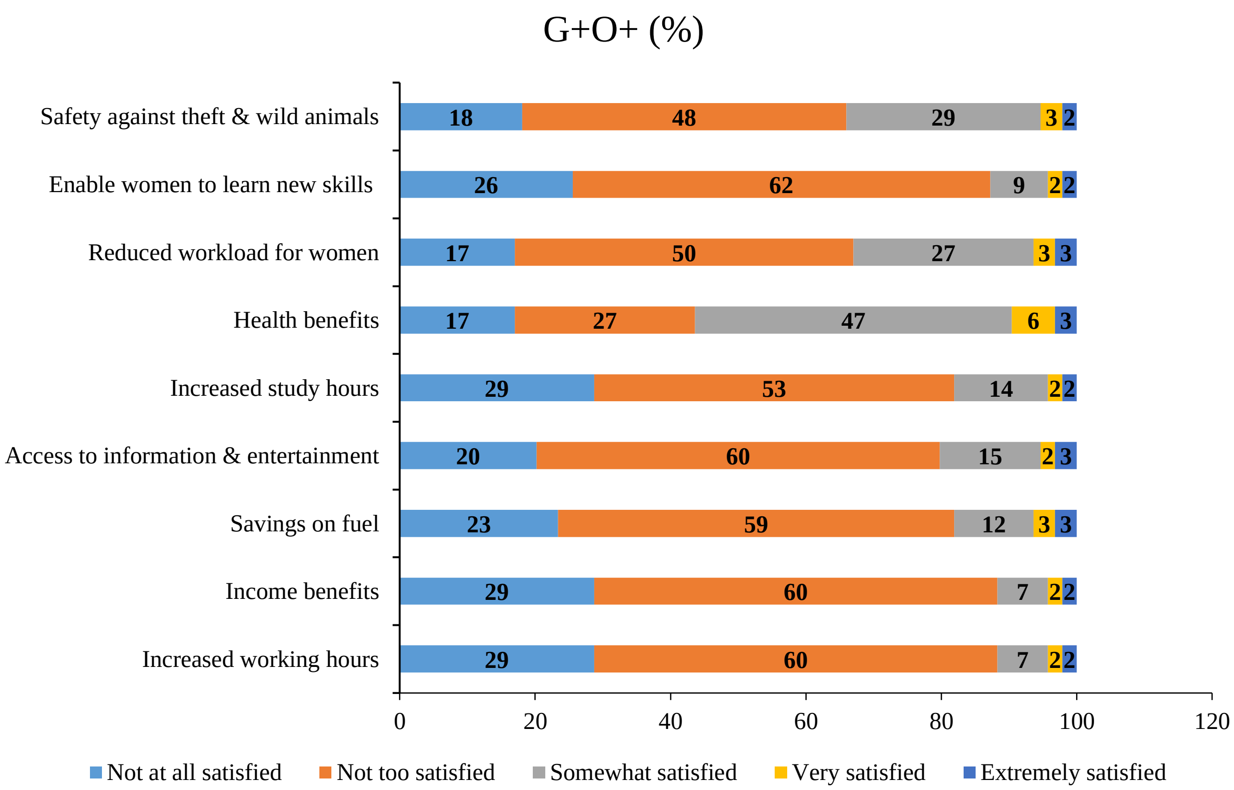


Fig. 5 (b): Satisfaction level with grid electricity in the household using both grid and off-grid solar.

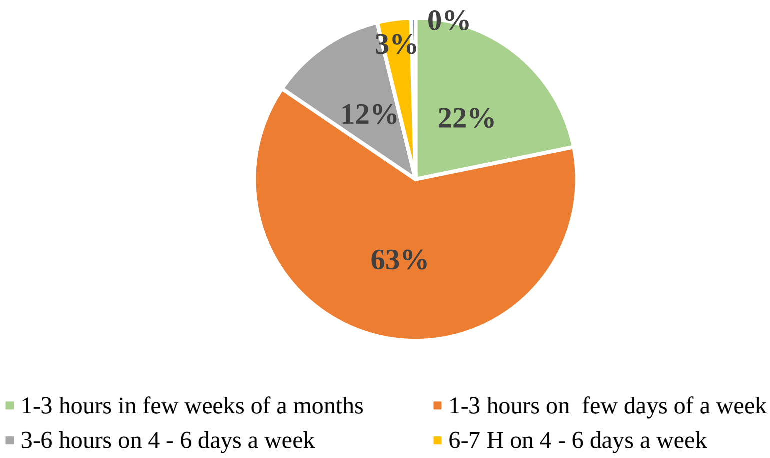


Fig 6: Grid electricity availability in sample households during evening hours (5 pm to 12 midnight).

We also explored the use of appliances and aspirations to own appliances in the surveyed households. We hypothesised that the aspirations of households for electrical appliances might offer insights on the potential demand for reliable electricity and consequent electrical retail opportunities. Fig 7 shows appliance use and aspiration in rural households including how it varied according to different levels of electricity access. On horizontal axis household appliance use is presented in percentage where; blue bar represents current use of appliance within surveyed households and their aspiration for new appliances is denoted in orange bar. Similarly, vertical axis shows appliances. Fig.7 (a) represents ongoing use (C) and aspiration (A) of appliances for all 731 households while Fig. 7(b), 7(c), 7(d) and 7(e) show breakdowns by household type. We found that individuals living in households aspire to own electrical appliances and this was independent of electricity access. As expected, grid-connected households (G+O+ and G+O-) owned the greatest number of appliances and households with both grid and solar power had the greatest range/number of appliances. Solar power users tended to use low wattage appliances for basic lighting, mobile phone charging and fans. Households without any access to electricity revealed a strong desire for owning electrical appliances of which lighting, television, electrical fan and washing machine were most aspired appliances. Overall, there is considerable potential demand for appliances across all types of households. From a supply perspective, the poor reliability of electricity and affordability for poor houses were the reasons that this demand could not be unlocked.

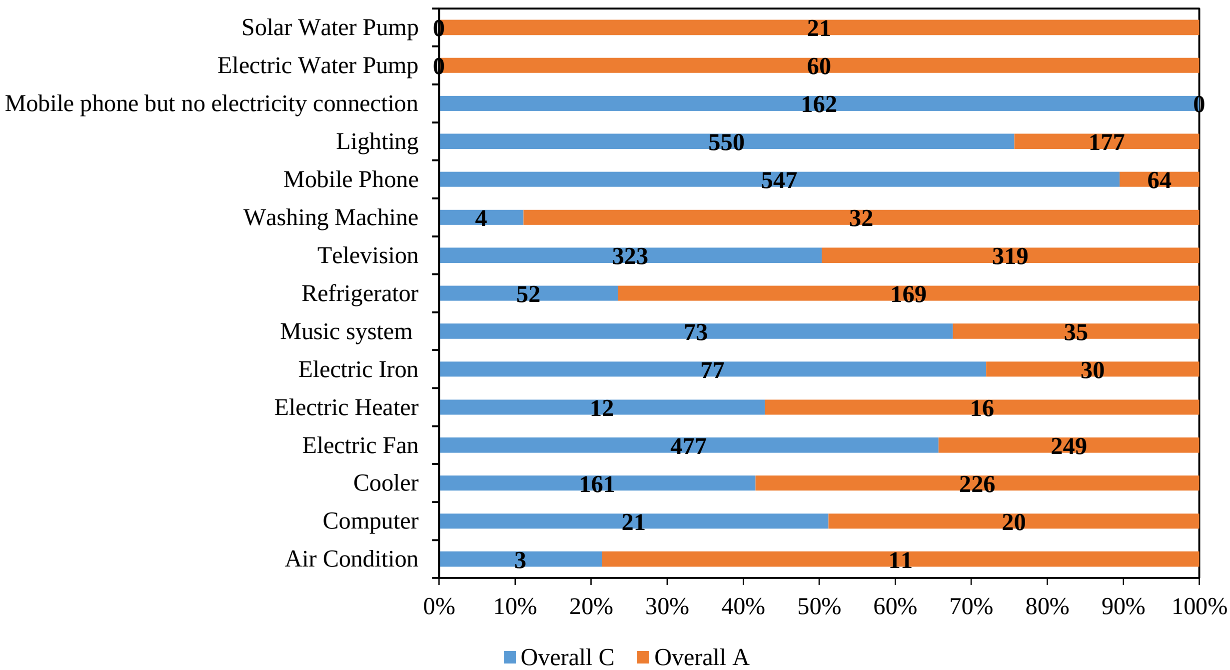


Fig 7 (a): Current appliance use and aspiration across all types of surveyed households.
Notes: The horizontal axis represents the per cent of household appliance use. Current use (Overall C) is denoted in the blue bars and appliances aspiration (Overall A) in orange bars for all 731 households participated in the survey.

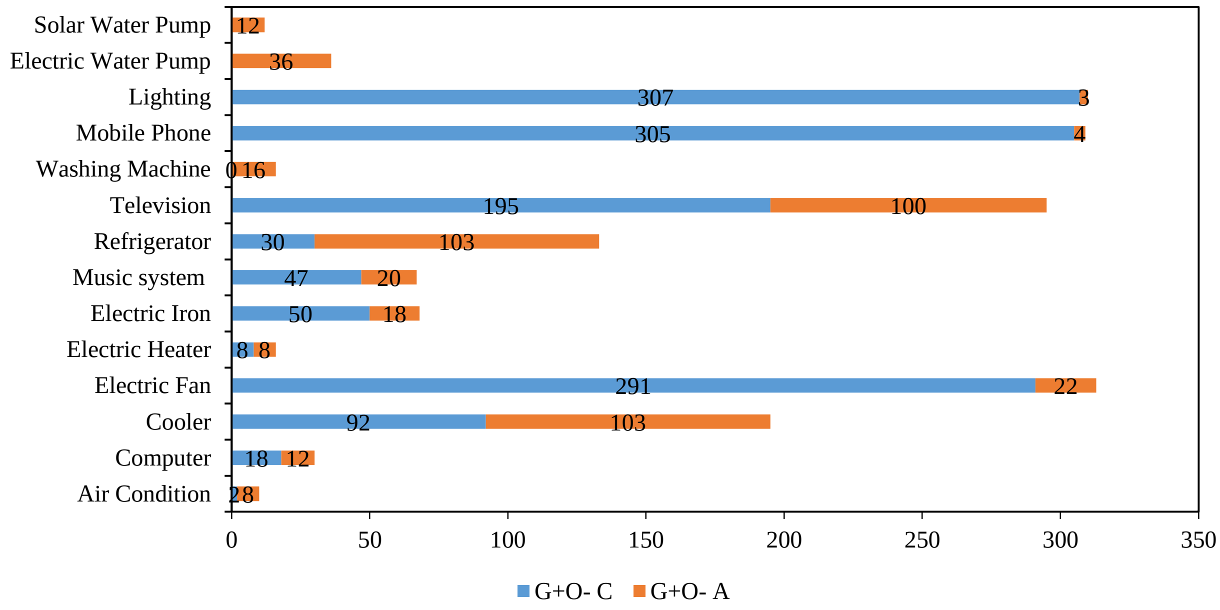


Fig 7 (b): Current appliance use and aspiration in households with a grid electricity connection (G+ O-).

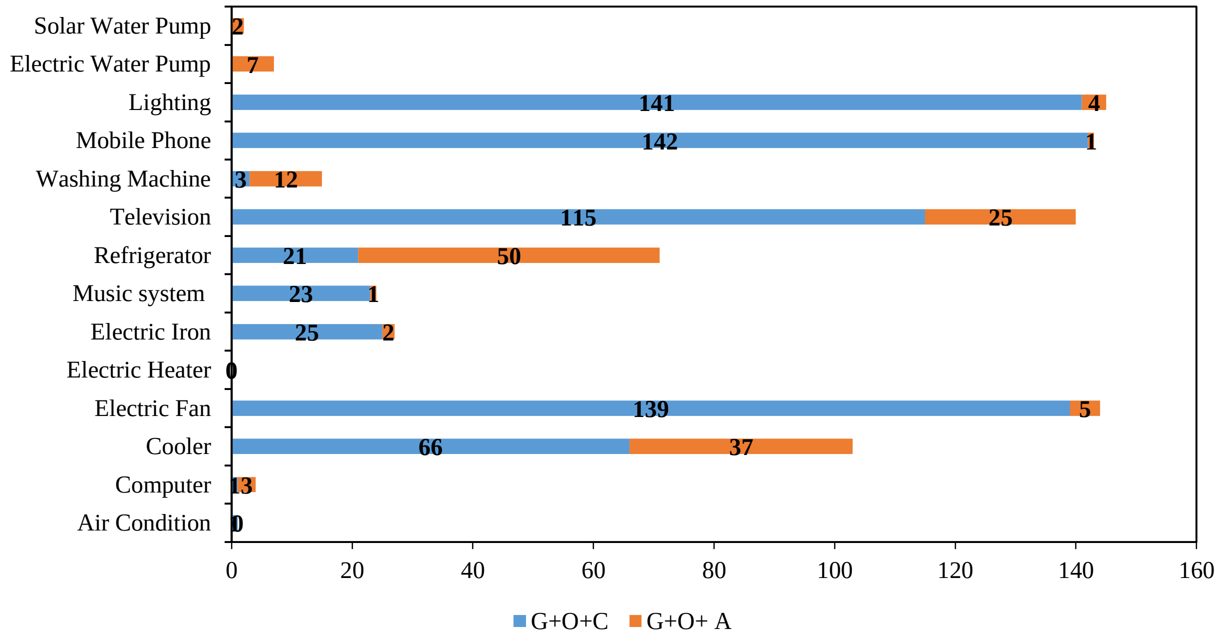


Fig 7 (c): Current appliance use and aspiration in households using both grid and solar electricity (G+O+).

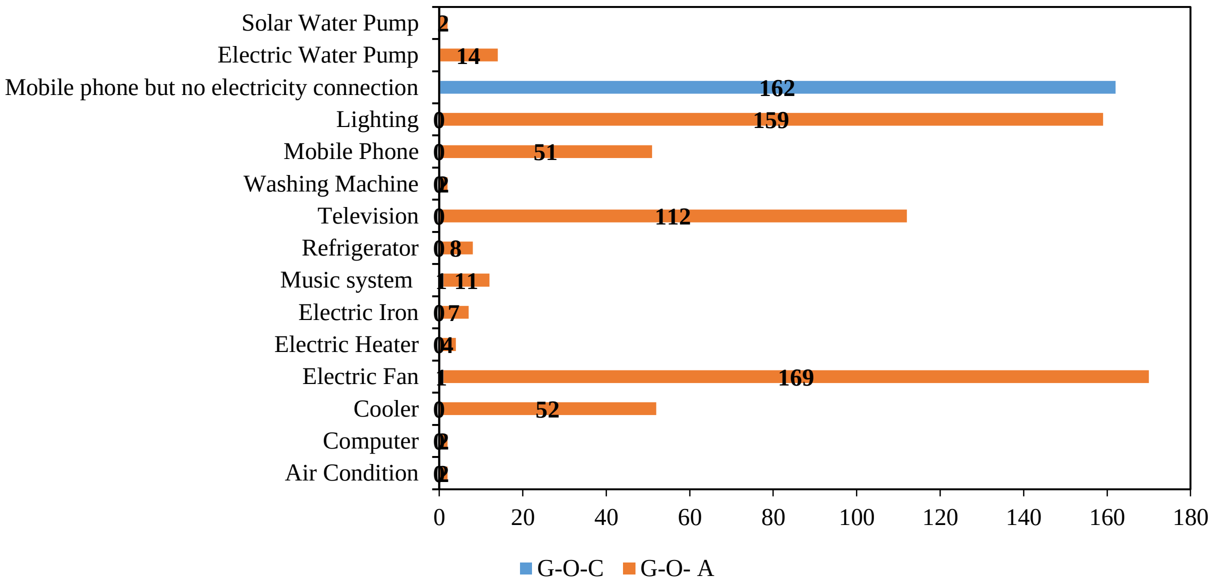


Fig 7 (d): Current appliance use and aspiration in households without any form of electricity (G-O-).

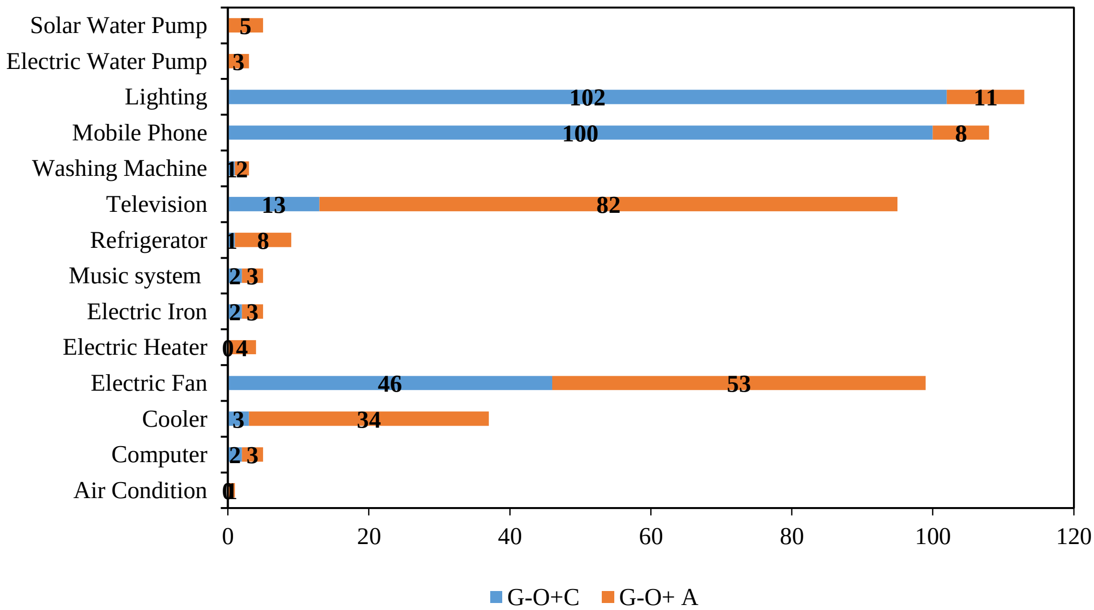


Fig 7 (e): Current appliance use and aspiration in households using solar power only (G-O+)

As our results suggest that fuel use at household level is dynamic and while fuel switching and stacking occur, this must be related to the activity requiring the energy. For this reason, appliance use, or aspiration will be directly linked to electricity, while cooling and heating is an application that can be satisfied with old and new forms of energy. Among various factors influencing fuel type and progression up the energy ladder, income and fuel availability are key factors driving household fuel choices. Therefore, the aim of an enabling household energy policy should facilitate the substitution of traditional fuels by making cleaner fuel (solar power and LPG) more affordable, whilst also cognisant of the cultural connections to biomass linked cooking. Furthermore, biogas presents a compelling renewable alternative to LPG in the context of rural communities in India where organic and bio-degradable wastes from cattle dung and biomass are more readily available to rural households. Therefore, as a decentralised energy source, biogas could feature as a more viable option in rural areas. Household-level biogas plants can offer dual benefits for rural households (at least for those primarily engaged in agriculture and livestock) as this cohort can 1) utilise their organic wastes to generate cleaner fuel and then reuse the slurry from the biogas plant as a soil conditioner in their farms; and, 2) biogas as cooking fuel can safeguard them from the more costly LPG, risk of fluctuations in prices of LPG and uncertainties of availability and access to LPG in villages.

Initiatives including government subsidies for promoting biogas plants, to date, have certainly helped a gradual deployment of biogas (MNRE 2020). In some states, an additional subsidy has been offered for toilet linked biogas plants aiming to offer remedies to both environmental and sanitation issues. However, overall adoption of biogas within rural communities continued to remain low due to combination of factors including poor awareness, high capital cost, the maturity of technology, varying feedstock availability and lack of consistent policy support (Mittal et al. 2018). During our household survey, we identified few households had used biogas in the past. These households anecdotally shared their experience on the use of biogas and stated that awareness about the technology, optimum use of wastes (in biogas plant), and available financial support remains poor among common village residents, also observed by (Raha et al. 2014). Where households (mainly wealthy) installed biogas plants, they stopped using them after few years because the systems were not reliably maintained (Boomlive 2015), that in turn offers a significant financial hurdle and an entry barrier for lower-income households, also noted by (Das et al. 2017). This implies the rural households, especially low income (if provided biogas plants through a public program) would likely revert to using traditional fuel in the absence of user education and support for ongoing maintenance. Like decentralised solar systems, biogas faces similar barriers in rural areas (Mittal et al. 2018) despite being a cheaper green alternative to LPG. This points to a need for creating an ecosystem where policy support and energy access efforts are targeted at overcoming known barriers and to enable the coordination of rural energy infrastructure to offer reliable supply chain and maintenance support. These critical factors should enable access to biogas as a cost-efficient alternative to LPG and ultimately support the transition of rural communities to a cleaner fuel.

Socio-energy inequality points to the critical need for such policies to prioritise rural communities and particularly poorer households where biomass use is higher to ensure the initial cost of energy transition and related equipment is supported and can be sustained within the financial limitations of this cohort. Similarly, cross-sector agriculture, rural development and energy policy synergies can further optimise transitions to create better living conditions, including cleaner indoor air pollution and to improve agricultural productivity through use of organic fertilizers. An interlinked policy framework can act to leapfrog the below poverty line population (annual income of US$ 390 or INR 27000) to cleaner fuels, rather than incrementally transitioning them up on the energy ladder via disconnected and often contradictory policies such as kerosene subsidies. Finally, the way forward can be the execution of policy choices that enable a bottom-up approach nested within a centralised governance framework and supported via localised implementation (Yadav et al. 2019). A private-public model could be used to leverage and dispense these policies for accelerating sustained deployment. This would primarily support those most in need and enable governments to achieve their UN sustainable development goals.

4. Conclusions

Energy policy in India is ever-complex due to crucial yet competing agendas of energy access and socioeconomic development in a carbon-sensitive world. Although the Indian government has embarked on a journey of climate and energy justice, it must compete with many other national issues including public health, nutrition, education, social and gender inequality. While energy access is a common thread to many of these problems, the inherent complexity has meant progress is slow and sometimes backwards. A “one size does fit all” approach does not apply to India and arguably many other developing and emerging economies due to its socio-economic and geographical diversity. While India has adopted a low carbon pathway, it still requires the retirement of old, and creation of new policies and robust governance frameworks that will allow effective delivery of multiple commitments. Energy policy in India, in particular, must explicitly recognise and incorporate economic variability (high, middle and low income), geographic variability (urban, rural and remote), technical variability (grid and off-grid) and institutional variability (public and private) in order to foster collaboration to produce the desired outcome at a lower cost and rapid pace.

In seeking to further understand fuel stacking, kerosene is incrementally replaced when grid electricity is provided with further reductions when solar power is available. Income is the most influencing factor that drives the transition to cleaner fuel use. However, as in the case of many parts of regional India, where there is high proportion of households below the poverty line targeted grants and subsidies can overcome this barrier.

There remains a socio-cultural connection to traditional fuels for cooking in rural India. It is anticipated that these fuel types will remain a part of the energy mix irrespective of the provision of cleaner and more efficient fuels. Rural communities are also heavily dependent on biomass, there exist opportunities to use farming wastes, currently diverted to energy, towards other enterprising activities such as organic fertilizer production. This switch in the use of this product can concurrently reduce indoor air pollution.

For a nation with 22 % of the population below the poverty line, energy policies must add value and provide compatible outcomes with other socio-economic and environmental goals. Fuel stacking is likely to remain a reality for India’s rural communities and therefore policies need to work within the social, cultural and economic drivers that perpetuate multiple fuel use, albeit with an eye to a cleaner energy future. In the short term, prospective policies must unwind contradictions, such as kerosene subsidies, that reinforce the carbon lock-in impacting on energy transitions. Similarly, the policy landscape must acknowledge the changing face of the energy sector in India and support new business models, diverse technologies and leverage new partnerships to bring broader capabilities to address energy challenges.

Acknowledgement

We extend our thankfulness to Mr. Sudhir Kumar Verma (Director, UPPCL) for his support in obtaining local contacts to conduct household surveys. We are also grateful to our interview participants for their time and support during the survey interviews. Prabhakar Yadav is thankful to Dr. Sabah Abdullah and extends his gratitude to her for providing direction on the research questions.

Funding

This work is supported by an “Australian Government Research Training Program Scholarship” received in 2016 and the department funding from the Department of Environmental Sciences, Macquarie University.

Appendix A: Information collected from respondents during the survey (list of questions used in this paper)

1. Relationship to household head?
2. What is your gender?
3. What is your age?
4. What is the highest level of education you have completed?
5. How many people currently live in your household?
6. How many members in the household are currently studying?
7. What is your approximate average household annual income?
8. Which of the following categories best describe your employment status?
9. What electricity source do you use in your household?
10. What household appliances do you currently use that require electricity?
11. What is your current approximate monthly expenditure on energy usage for household purposes?

12. Please rate the availability of grid electricity in your household between sunset and midnight (5 pm to 12 o'clock midnight).

13. If you are an electricity user, please rate your experience of using grid electricity.

14. Which of the appliances would you use, if you could get access to electricity, or reliable electricity supply?

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