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Thermo-electric generation (TEG) enabled cookstoves in a rural Indian community: a longitudinal study of user behaviours and perceptions

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Supplementary material for this article is available online

Abstract

Background. Traditional cookstoves that burn solid biomass are associated with inefficient burning, a high degree of household air pollution and high morbidity rates. A key barrier to the adoption of clean cookstoves has been the cost of fuels. Hence, a Thermo-Electric Generating (TEG) cookstove that used solid biomass fuels more efficiently and released less smoke was developed. The TEG cookstove also generates electricity to power small electric devices. Fifteen TEG cookstoves were distributed to villagers in the Indian state of Uttarakhand in 2019. *Objective*. We wanted to understand whether, after two years of distribution, TEG cookstoves were still used, what and where they were used for, their perceived impacts on health, and the barriers to their use. *Methods used*. We surveyed 10 of the 15 recipient households. We applied the Capability, Opportunity, Motivation-Behaviour and Behaviour Change Wheel frameworks to understand what the barriers to adoption were, and what could be done to surmount these. *Results*. All respondents reported lower smoke levels and most respondents reported that the TEG cookstoves required less fuelwood than their traditional cookstoves, but none had used them in the month prior to the survey. *Discussion*. For those whose TEG cookstoves were still usable and had not been made redundant by clean cookstoves, we found there to be physical opportunity barriers and psychological capability barriers. Physical opportunity barriers included a small inlet for fuel, limited versatility beyond cooking at low temperatures, and the availability of only one hob. To surmount these barriers, we recommend co-design to suit user needs and education emphasising visible benefits of avoided soot on kitchen walls, in addition to the health benefits.

1. Introduction

In 2018, 2.8 billion people globally were relying solely on traditional polluting fuels and earthen and brick cookstoves for cooking—a number largely unchanged over the past two decades, in spite of almost three decades of interventions to move people to clean cooking. This is due to population growth outpacing the proportion of

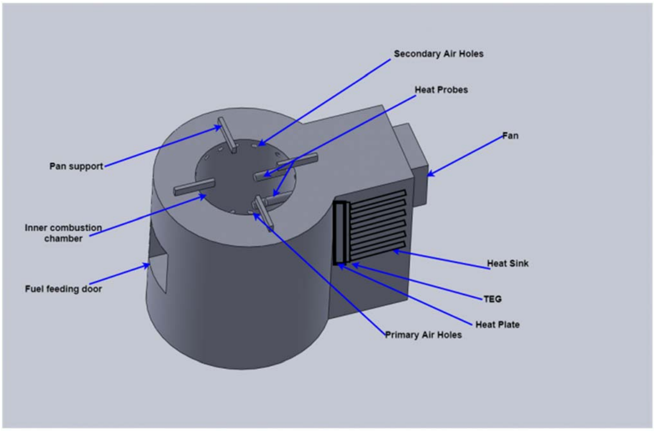

Figure 1. Design of TEG cookstove by IIT Delhi. *Source: IIT Delhi.*

people gaining access to clean cooking fuels, but also due to lack of clean cooking adoption (IEA *et al* 2020, Zakaria 2021). It is estimated that unclean cooking costs the world more than USD2.4 trillion each year, driven by adverse impacts on health (USD 1.4 trillion); lost productivity from time spent collecting fuel, stove cleaning and cooking for up to six hours per day(USD 0.8 trillion); and from greenhouse gas emissions from inefficient fuel combustion (USD 0.2 trillion) (ESMAP 2020). Beyond the climate impacts of using biomass, there are also concerns that the collection of fuelwood for traditional cookstoves leads to forest degradation and deforestation and that the use of dung for cooking rather than for fertilising leads to foregone agricultural productivity (ESMAP 2020).

To address concerns about deforestation and fuel scarcity, interim 'improved' stoves were promoted in India and China in the 1980s and 1990s to surmount the financial barrier to adoption of clean cookstoves, and achieve greater burning efficiency than that which was achieved by traditional earthen or brick cookstoves or open fires (World Health Organization 2016). Unlike 'clean' cookstoves which meet the World Health Organization's limits on particulate matter ($PM_{2.5}$) and carbon monoxide (CO) emissions rates (World Health Organization 2016, Annex 3),[9] improved cookstoves stoves use solid biomass fuel. Clean cooking has thus far not been achieved with the combustion of biomass or other solid fuels such as charcoal, but rather with the use of electricity, gas, and alcohol.

Widespread dissemination of improved cookstoves was also impeded for several reasons, and the better health outcomes were limited. Whereas improved cookstove programmes have emphasised fuel economy, users have regarded versatility and the ability to cook quickly as more important (Gill 1987). Nor were improved cookstoves necessarily more efficient, nor were they always smokeless; indeed progress made in alleviating the burden of disease from household air pollution associated with burning solid fuels for cooking has been modest (Gill 1987, Smith and Sagar 2014, World Health Organization 2016).

In spite of decades of efforts to make biomass fuel clean through advanced stoves, modest progress had been by 2014 (Smith and Sagar 2014). On the premise that improved cookstoves are likely vehicles for positive health impacts for those unable or unwilling to pay for fuel for clean cookstoves, engineers have been continuing to develop improved cookstoves. One such improved cookstove is the thermoelectric generating (TEG) cookstove. Not only is it meant to burn solid fuel more efficiently than traditional cookstoves, but the thermoelectric generation component is designed to reduce polluting emissions by using a small direct current-powered fan that drives air inside the cookstove to improve combustion (Mal, Prasad and Vijay 2016). In so doing, the TEG cookstove potentially addresses several of the United Nations Sustainable Development Goals (SDGs): SDG 3 (good health and well-being) and SDG 7 (affordable and clean energy). By reducing time to collect fuelwood and reducing fuelwood collected, it also supports SDG 10 (reducing inequalities), as well as SDGs 13 and 15 (climate action and life on land) and SDG 8 (decent work and economic growth).

Engineers at the Indian Institute of Technology, Delhi (IIT Delhi) Centre for Rural Development Technology developed such a cookstove—see figure 1. In laboratory conditions, the TEG cookstove delivers improved efficiency with which biofuel is burned (eucalyptus wood was burned in the laboratory), boiling 6.1 litres of water within 30 min, thus reducing both the fuel required as well as emissions (Mal *et al* 2015). It also generates 3–5W electricity to charge small electric devices such as mobile phones and lights (Mal *et al* 2015). The World Bank Energy Sector Management Assistance Program have developed a Multi-Tier Framework for

[9] Unvented PM2.5 limit is 0.23 mg min^{-1}, 0.8 mg min^{-1} for vented. Unvented CO limit is 0.16 g min^{-1}, 0.59 g min^{-1} for vented.

assessing the quality of measuring access to cooking solutions and for measuring access to electricity. Tier 0 is the lowest quality tier and tier 5 the highest. The IIT Delhi team designed the TEG cookstove to fall in tier 4 for thermal efficiency, tier 4 for carbon monoxide emissions (3.75gCO/MJ energy delivered), and tier 3 for particulate matter emissions (124mgPM/MJ energy delivered). Electricity produced, which was meant to be an added benefit, was anticipated and assessed to be tier 0 for the quality of electrification, equating to less than 12Wh of electricity produced per day. The cost of a biogas cookstove can be as little as USD 5.50, but a biomass cookstove designed for burning fuelwood will cost USD 23 (indiamart 2022a, 2022b). (A traditional cookstove can be made at home free of additional financial cost using mud or repurposed bricks.) The TEG component costs an additional USD30-USD50 to produce per unit (depending on model design) if 1,000 units are manufactured (Mal *et al* 2016).

Through an exploratory pilot, IIT Delhi distributed 15 prototype TEG cookstoves to 15 village households in the Indian state of Uttarakhand in 2019. The provision of these cookstoves was initially funded by the Unnat Bharat Abhiyan programme, an Indian Human Resource Development Ministry initiative to economically develop self-sustaining villages using decentralised, eco-friendly technologies that would reduce ecological degradation, improve health outcomes, while enabling food and energy needs to be met locally (Ministry of Human Resource Development, IIT Delhi and Unnat Bharat Abhiyaan 2018). Funding was supplemented by India's Oil and Natural Gas Commission scheme.

In this study, we sought to follow-up with those households in 2021 to understand whether, after two years of distribution, TEG cookstoves that used solid biomass were still used, what they were used for, where they were used, what their perceived impacts on health were, and what the barriers to their use were.

2. Literature review

2.1. Why traditional cookstoves are problematic

Unclean cooking contributes to poor health, both among users as well as among children and babies yet to be born. Unclean cooking causes household air pollution when done in or near indoors, particularly when there is inadequate ventilation. Diseases arising from household air pollution account globally for an estimated 1.8 million to 4 million deaths annually and 60.9 million disability life adjusted years (DALYs) (IEA *et al* 2020, Lee *et al* 2020). In their systematic literature review, Lee *et al* found that chief amongst the causes of death are respiratory diseases, accounting for 38% of deaths and 75% of DALYs, and among these, communicable respiratory disease (acute respiratory infection and pulmonary tuberculosis) accounted for most of the respiratory burden, followed by chronic respiratory disease (asthma and chronic obstructive pulmonary disease) and then lung cancer (Lee *et al* 2020). Cardiovascular disease (ischaemic heart disease and cerebrovascular disease) accounted for most of the remaining deaths and DALYs (Lee *et al* 2020). Other conditions associated with household air pollution include strokes and diabetes (Balakrishnan *et al* 2019). Among those with an increased risk of mortality are children under the age of 5 (Lee *et al* 2020). Negative health effects extend to new-borns: infants born to mothers exposed to polluting fuels and technologies are lighter and at greater risk of stillbirth (Lee *et al* 2020).

Collection of fuelwood as a driver of forest degradation and deforestation is also a concern that has motivated governments such as India and China's to move traditional cookstove users towards more efficient improved cookstoves (Rademaekers *et al* 2010, World Health Organization 2016). A study of household and personal air pollution among 811 rural households in India showed that of biofuels, wood was the most popular. Three hundred and eighty-three (383) households used wood, 80 used animal dung and 2 used agricultural or crop waste (Shupler *et al* 2020). Low levels of efficiency associated with traditional cookstoves prompt additional use of biomass. Women and children also lose time collecting additional firewood from long distances (Patowary and Baruah 2019).

These non-health related arguments against traditional cooking have been critiqued. There have been questions raised over the relative impact of fuelwood collection on deforestation by rural households against the impact of urban consumption and production systems (Zakaria 2021). These critiques extend to the argument about 'lost' productivity and whether traditional cookstove users wanted to exchange their time spent on fuelwood collection which can embed exercise, fresh air, and socialising without any questions raised—for exploitative wages (Zakaria 2021).

2.2. Barriers to adoption of clean cookstoves

While cleaner cooking fuels such as liquefied petroleum gas (LPG) are both popular and positively regarded among both users and non-users as convenient and clean, affordability is a barrier in replacing traditional biomass (Gould and Urpelainen 2018). According to the 2011 Indian census, only 11% of rural households had adopted LPG as a cooking fuel (Tripathi, Sagar and Smith, 2015, Gould and Urpelainen 2018). An Indian government programme called Pradhan Mantri Ujjwala Yojana (PMUY) distributed 70 million LPG stoves within its first 35 months, starting in 2016. LPG sales data showed that the rapid growth in enrolment in LPG consumers was not matched by an increase in LPG sales, and that the volume of LPG sales among PMUY beneficiaries was less than half that of general rural consumers (Kar *et al* 2019). Further analysis showed seasonality depending on when cash was most available (i.e. during the harvest season) and when time was most constrained (i.e. during the cropping season) (Kar *et al* 2019). Another study involving semi-structured interviews with PMUY beneficiaries in a district in Karnataka revealed that respondents perceived the main value of LPG to be time saving, rather than better health (Cabiyo, Ray and Levine 2021). Further reviews of the literature have revealed further nuance in affordability as a barrier: there is the high initial cost of clean cookstoves; volatility of LPG price linked to oil markets; irregular family income to pay for regular fuel expenses; and females neither control the household money nor the mobile phone to order timely refills (Kar and Zerriffi 2018, Cabiyo, Ray and Levine 2021).

Recognising the financial barrier to using non-biofuel cookstoves, many interventions aimed at reducing household air pollution from the combustion of solid fuels for cooking have therefore focused on the adoption of improved wood-burning cookstoves, i.e. cookstoves that burn free-of-financial cost biofuel more efficiently (Gould and Urpelainen 2018). One study found that improved cookstoves required 20%–30% less firewood than traditional stoves (Bensch, Grimm and Peters 2015).

2.3. Adoption of improved cookstoves and value addition

Even with improved cookstoves running on free biomass, and even once they have overcome the barrier of purchasing a cookstove (Mobarak *et al* 2012, Wilson *et al* 2018), poor communities do not completely abandon their traditional biofuel stoves: instead they practice stove stacking which involves the use of multiple stoves in a household (Chalise *et al* 2018). It has been hypothesised that reasons for stove stacking include taste preferences associated with traditional cookstoves, as well as community or society-wide norms and traditions (Bensch, Grimm and Peters 2015). Indeed, in the rural Indian context in the rural and poor district of Kalahandi, Odisha, researchers found that while 100% of 72 users given improved cookstoves that ran on free biomass for a two week trial preferred to prepare tea on the improved cookstove, and a high proportion used it for cooking upma (96%), khichdi (75%) and curry (71%), a low proportion preferred it for other dishes including dal (31%) and rice (6%) (Wilson *et al* 2018). This demonstrates a difference in use for differing dishes. Overall, only 19% of households used the improved cookstove as the main stove for cooking (Wilson *et al* 2018).

Besides stacking, maintenance of improved cookstoves is a barrier to regular use. In a randomised trial across 2,575 households in 44 villages in Orissa, India, Hanna, Duflo and Greenstone (2016) found that use of improved cookstoves declined markedly. They attributed the decline in use to lack of maintenance investments necessary to keep the cookstoves fully operational. As a result of the low use in year three, Hanna *et al* found no statistical difference in health outcomes, emissions or deforestation between users who had been given improved cookstoves and those who had not. They did note, however, a significant reduction of smoke inhalation during the first year for the primary cooks in the household. The results highlighted that new technologies require testing in real-world settings to assess whether behaviour may undermine the intended impacts.

2.4. A framework for analysing adoption barriers

Williams *et al* (2020) pioneered the application of the Capability, Opportunity, Motivation-Behaviour (COM-B) framework together with the Behaviour Change Wheel (BCW) and Theoretical Domains Framework (TDF) to inform the evaluation of theory-informed strategies to promote exclusive clean cookstoves.

As a theoretical framing, COM-B (Michie, Van Stralen and West 2011) is an appropriate lens with which to explore household use of cookstoves—see figure 2. The model proposes that behaviour will take place only if salient capabilities, opportunities and motivations are in place. It has been applied widely in the domains of health and environmental behaviour, including energy use. COM-B recognises the importance of factors both within and external to the individual. Capabilities are factors internal to the individual, including physical assets such as strength or dexterity, and psychological resources such as knowledge. Features of the external context, both physical (such as availability of an energy-efficient cookstove) and social (such as cultural norms), are considered as Opportunities. Opportunity and Capability contribute directly to behaviour in the model but, critically, also indirectly contribute through Motivation. Motivation is the driving force for a behaviour and encompasses conscious processes such as planning and decision-making as well as automatic processes such as habit and emotion-guided choices. Motivations determine not only whether a behaviour will happen, but also whether the behaviour will persist over time.

Following application of the COM-B model to identify adoption barriers, the Behaviour Change Wheel (BCW) is often used to suggest appropriate interventions to overcome these barriers. Figure 3 shows interventions highlighted in red, many of which are self-explanatory, but some of which require some

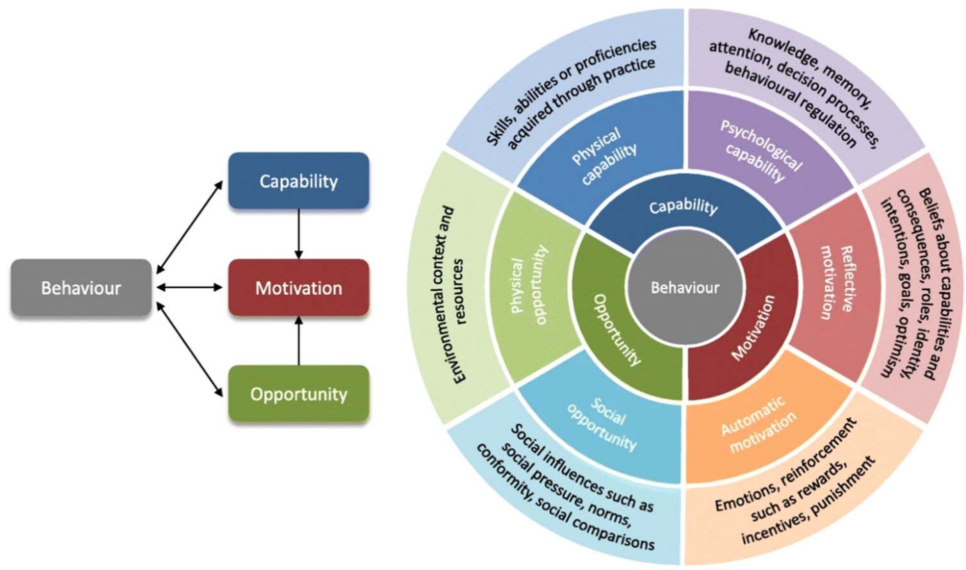

Figure 2. The Capability, Opportunity, Motivation, Behaviour (COM-B) framework with definitions. *Source:* McDonagh *et al* 2018.

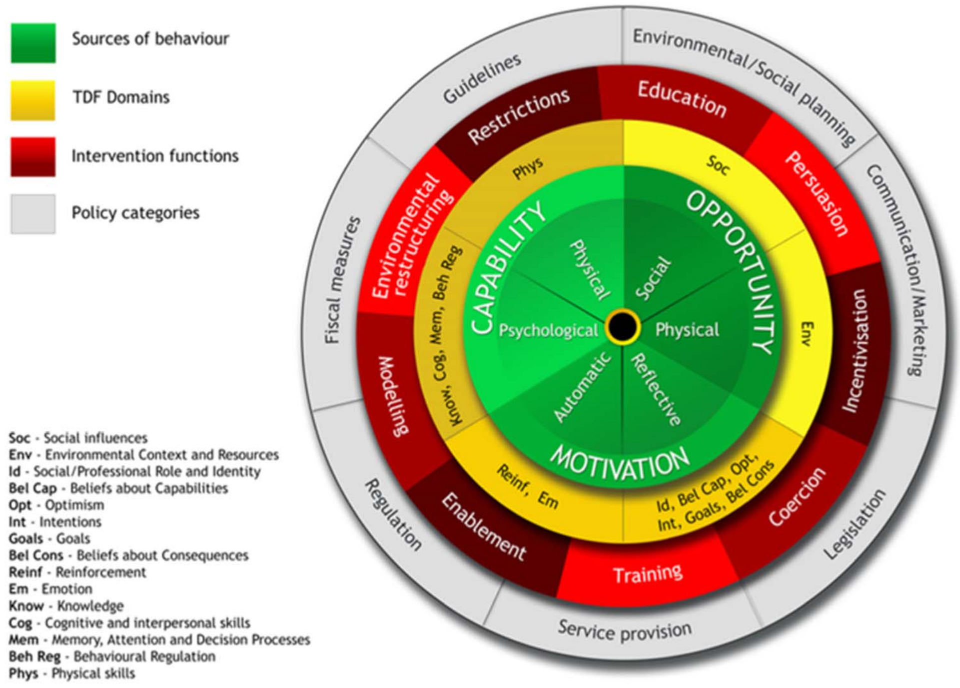

Figure 3. Overlaying the COM-B framework with the Behaviour Change Wheel (BCW) which points to interventions. *Source*: Younas and Gutman 2022.

explanation due to overlaps: education increases knowledge or understanding, while training imparts skills (Michie and Atkins 2014). Enablement means increasing or reducing barriers to increase capability beyond education and training, or to increase opportunity beyond environmental restructuring, which means changing the social or physical context (Michie and Atkins 2014). Modelling refers to providing an example for people to aspire to (Michie and Atkins 2014).

Williams *et al* (2020) collected data using in-depth interviews, focus group discussions, observations, key informant interviews and pilot studies to identify key influencers of cooking behaviours. Of interest to them was the impact of exclusive use of LPG as a cooking fuel on air pollution exposure and health of pregnant women, older adult women and infants under the age of one in Guatemala, India, Peru and Rwanda. They identified nine potential influencers of exclusive LPG use in cookstoves: perceived disadvantages of solid fuels, family preferences, cookware, traditional foods, non-food-related cooking, heating needs, LPG awareness, safety and fears, and costs and availability of fuel. They matched these influencers to the barriers in the Capability, Opportunity, Motivation framework. Their key findings were that messaging about health benefits is less effective than messaging that emphasises the immediate visible disadvantages of cooking with solid fuels, such as dirty kitchens; use for non-food related cooking and for heating were key influencers of LPG cookstoves' exclusive use; and compatibility with traditional foods was a predictor of exclusive LPG use in cookstoves.

Williams *et al* did not specify when they conducted their data collection relative to the distribution of the LPG cookstoves, but it does not seem that there was a significant time lag between the two events. Their study also did not extend to TEG cookstoves which use the same solid biomass fuel that traditional cookstoves do.

Most recently, Perros *et al* 2022 conducted a structured literature review of 100 papers to identify drivers of fuel stacking as an impediment to the full adoption of clean fuels. They then mapped stacking drivers onto the COM-B model. They found that the Physical Opportunity domain accounted for 82% of drivers. The most common of these drivers were fuel price being too high, particularly for LPG; broken equipment; and incompatibility of stove with large pots. For improved cookstove users, the Physical Opportunity driver for stacking was frequently attributed to the stove being too small and therefore unable to support large cooking pots. Psychological Capability accounted for 3% of drivers relating to the cook not knowing how to use stoves correctly. It was more pertinent for electric cooking than for other technologies—for example, not knowing how to cook roti on an induction stove.

2.5. Development of the TEG cookstove, and predictors of their adoption

Facing financial costs, stacking and maintenance barriers to adoption, technology developers have strived to offer a more compelling proposition by adding to improved cookstoves the added benefit of electrical charging for mobile phones, lights and radios. While access to electricity is now almost universal in India with more than 99% of the population recorded as having access as of 2019 (IEA 2020), reliability and quality of power delivered remain areas for improvement. On a scale of 1 to 7 with 1 being extremely unreliable and 7 being extremely reliable, the World Economic Forum scored India's electricity quality 4.7 (WEF 2019). Moreover, the majority of power outages occur during peak demand hours (Patowary and Baruah 2019). Due to irregular access to electricity at home, and surging demand for charging mobile phones, ights and radios, it is common for people to travel distances and pay money to charge their battery powered devices and mobile phones. People pay up to 450 times the price of residential consumer grid electricity in Delhi to charge their phones at kiosks in rural Odisha (Wilson *et al* 2018), where the annual average per capita electricity consumption is 1,628 kWh (Government of India 2019). Against a context of irregular access to electricity at home, the developers of TEG cookstoves hope that adding a USB port for electrifying mobile phones and LED lights will incentivise adoption for their healthier cookstoves.

To generate electricity, these improved cookstoves with electricity generating capabilities, called thermoelectric generating (TEG) cookstoves, use the difference in temperature between two semiconductor blocks inside a cookstove to produce voltage. Voltage (V) is directly proportional to the temperature difference (ΔT) and Seebeck constant (α), $V = \alpha \text{ x } \Delta T$ (Mal *et al* 2015, Patowary and Baruah 2019). Forced air by electric fans improves combustion and reduces harmful emissions (Wilson *et al* 2018).

Amongst the first studies assessing the feasibility of TEG cookstove prototypes was a series of papers studying their deployment in Malawi. An 80-day pilot study in 2014 with four households in Balaka district in Malawi suggested that the generators performed adequately in charging LED lights and mobile phones (O'Shaughnessy *et al* 2014). A subsequent pilot of 10 TEG cookstoves in Ntcheu district with 4W of electric power using significantly less expensive and more robust components was tested for 6 months (O'Shaughnessy *et al* 2015). A third study involving five households in Thyolo district found the successful ramping up of power was capable of generating 10Wh for charging (Deasy *et al* 2018).

In the Indian context, Wilson *et al* (2018) pioneered assessing the adoption of, perceptions of and willingness-to-buy or rent TEG cookstoves. They distributed TEG cookstoves to 72 households across 3 villages without electricity access in the district of Kalahandi in the state of Odisha for a 2-week trial. To measure the impact of the USB charging port, they randomised half of recipients to receive a TEG cookstove with the USB port disabled, and the other half of recipients to receive a TEG cookstove with the USB port enabled. What users liked most about the TEG cookstoves was that it emitted less smoke, that it had a USB port and that it enabled fast cooking. What they liked least about TEG cookstoves was the limited fuel loading, its size and the limited volume of food they could cook at a given time. Respondents gave size, stability and fuel preparation an average score of 3.8 to 3.9 out of 7. Those with the USB ports enabled used their TEG cookstoves statistically significantly more than those with their USB ports disabled: 63 min versus 19 min on average per day. Overall, the TEG cookstove was perceived to be a poor direct replacement for earthen cookstoves, with only 19% of respondents preferring it for their main cooking, although as observed above, they did prefer it to make tea and a few other dishes.

After a 30-minute training on how to use the TEG cookstove, 67% of recipients in Wilson et al (2018) study said they would be willing to pay a mean average price of 360 rupees (USD 5.20 in 2018) for the TEG cookstove with the USB enabled and 67% of recipients aid they would be willing to pay a mean average price of 342 rupees (USD 5.07 in 2018) for it without the USB. This implies that users valued the USB feature at USD 0.13, and that the price they would be willing to pay for a TEG cookstove is below the price of biomass cookstoves available on the market. This seems inconsistent with the much greater use of the stoves with the USB feature, and it might be that users of the USB feature are expressing a maximum willingness-to-pay that is guided by what is affordable to them. The low willingness-to-pay is consistent with the findings of Mobarak et al (2012) that willingness-to-pay for improved cookstoves can be very low in rural South Asia. In contrast, however, 47% of recipients at the time of the baseline survey said they would be willing to rent the TEG cookstove with the USB enabled for 27 rupees per week, representing an annualised rent of 1,404 rupees (USD 20.50 in 2018), and those with the USB disabled for 25 rupees per week (USD 18.98 on an annualised basis in 2018). While the willingness-to-pay results do not suggest commercial viability, the willingness-to-rent results, where the annualised price paid is five times the purchase price, show a way forward for how the costs associated with making a TEG cookstove can be recouped.

Wilson et al (2018) carried out two surveys: one after a 30-minute training and one after a two-week trial, O'Shaughnessy et al (2015) surveyed respondents after two months of trial and Deasy et al (2018) surveyed respondents after several days of trial. However, we know from Hanna et al (2016) that the use and therefore impact of a new improved cookstove can decrease over time. This principle can be generalised more broadly as the impact of new technologies on consumer behaviour and therefore on desired outcomes often diminishes over time (Stewart et al 2013). The current study is the first to our knowledge to assess barriers to adoption of TEG cookstoves over a prolonged time horizon. Previous studies also did not look at the non-cooking and non-electricity uses of the TEG cookstove, where it was used, what impact it had on specific health indicators related to household air pollution, the impact it had on children's health and what sorts of biofuel were commonly used.

Our research objectives were to cover areas that the literature did not for TEG cookstoves that used solid biomass, and after two years of distribution, to address the following research questions:

1. What were the non-cooking and non-electricity uses of the TEG cookstove?
2. Where were the TEG cookstoves used?
3. What were the TEG cookstoves' perceived impact on health?
4. What were the barriers to adoption?

3. Methodology

Through its partners, as an exploratory pilot, IIT Delhi distributed a total of 15 prototype TEG cookstoves to 15 households in June and August 2019 in the rural village cluster of Gaindikhata (see figure 4) where people used wood for cooking. The village cluster includes Gaindkhata, Ahmadpur, Chidyapur, Lahadpur, Naurangabad and Pilli Padao, has a population of less than 7,000 people, and is located in district Haridwar in the state of Uttarakhand.

Of the 15 TEG cookstoves distributed, four had been distributed free of cost under the Unnat Bharat Abhiyan initiative to the senior most women of the household. Upon seeing relatively smokeless demonstrations of the TEG cookstove in the villages of Gaindikhata and Naurangabad on 3 July 2019, villagers in the area had requested to use them in their homes. The inclusion criteria for being eligible were those using only biomass and traditional stoves for cooking their daily meals; and who could not afford the stove. The inclusion criteria did not include being connected to the electricity grid since almost all Indian households are recorded as having access to electricity. Due to further demand from villagers, 11 more were sold at a subsidised fifth of the cost with support from the Oil and Natural Gas Commission scheme, for 1,000 rupees (USD 14.60 at the time) per cookstove. The same inclusion criteria were apparently applied.

To explore how successful the pilot was, we surveyed the households in 2021 to understand behaviour and perceptions around the use of TEG cookstoves, barriers to adoption and whether users practiced stove stacking (i.e. used their traditional cookstoves in addition to using the TEG cookstoves). Specifically, we explored whether households still used the TEG cookstoves after two years, how often, for what, what the impediments to use were, and whether users would be willing to purchase or rent replacement cookstoves in the event that they no longer had TEG cookstoves. We also explored whether the TEG cookstoves may have had a positive impact on the health of the primary cookers and children of the household.

We conducted structured interviews with two-thirds of the households which had received their cookstoves two years earlier. Nine (9) users were interviewed face-to-face in September 2021 and one (1) additional household by telephone in November 2021. The remaining five households that were not interviewed were

Figure 4. Aerial view of village Gaindikhata from Google Earth. *Source: Map data ©2022 Google*.

contacted by telephone but could either not be reached or were unavailable. The 10 households were spread across four villages—three from Gaindikhata, two from Lal Dhang, three from Pili Padao and two from Naurangabad.

Data were collected, shared, stored and analysed in accordance with prior ethics committee approvals attained from University College London (UCL Project Ethics Identification Number 11769/002) and IIT Delhi (2021/P003). Preliminary analysis included checking that responses were congruent. In a small number of cases, the original questionnaire responses were checked to ensure accurate data entry. No data were collected from respondents under the age of 18. Informed consent was obtained from participants. The survey was co-developed by an interdisciplinary team including the engineering developers of the TEG cookstoves as well as researchers specialised in community child health, behavioural change and infrastructure.

The questionnaire written in English was translated into Hindi and piloted on campus at IIT Delhi using convenience sampling among the data collector's peers. It was accordingly shortened. It was designed to allow for descriptive statistical and inferential analysis. To assist with analysing the results with respect to adoption, we used the COM-B (Capability, Opportunity, Motivation—Behaviour) framework for understanding behaviour.

4. Results

4.1. Household and kitchen characteristics

The surveys were conducted two years after the TEG cookstoves were given to households. All respondents were over 18 years of age and female. The respondents were generally not very young women—the youngest was 21, and the eldest was 65. The mean age was 35, with a standard deviation of 10 years. Three were aged 25 or younger.

The incomes of the ten households varied greatly, with a self-reported range of Rs 1,111 (USD 15)/month to more than Rs 30,000 (USD 400)/month. Farming was a source of income for seven households, self-employment and business for three and salaried jobs for three (these results were not mutually exclusive).

As table 1 above shows, the modal number of rooms in the respondents' households was three rooms, the minimum being two rooms and the most being five rooms. All of the ten households reported having their own grid connections for electricity. One household had 11 residents—it had two rooms. The other household sizes varied from two to nine people, with an average of 5.8 rooms across all of the houses.

No kitchens for the households were in the same room as where people slept or where the head of house spent time relaxing and socialising, i.e. kitchens were separate from bedrooms and living rooms. No kitchens were located outdoors, although outdoor cooking did occur (see figure 5).

Table 1. Survey results for household and kitchen characteristics.

Household and kitchen characteristics					
# rooms in house	# responses	Location of the kitchen	# responses	Normal indoor/outdoor cooking	# responses
1	0	Same room as where people sleep	0	All outdoors	1
2	2	Same room as where people relax/socialise	0	Mostly outdoors	0
3	6	Separate from bedroom & living room	9	About equal	0
4	1	Outdoors	0	Mostly indoors	5
5	1	Total	9	All indoors	4
Total	10			Total	10
Vents for indoor cooking	# houses	**Weather affects choice of in or outdoors**	# responses	**Where the TEG cookstove was used (when it was used)**	# responses
Chimney	1	Yes	1	Outdoors	4
Hole in the wall	4	No	8	Indoors	2
Window	1	Total	9	Both	3
Door	9			Total	9
<4 walls	0				

One household reported cooking outdoors all the time. Five (half of) households reported cooking both indoors and outdoors, although mostly indoors, and four reported cooking only indoors. Only one of nine respondents said that the weather affected whether they cooked in or outdoors. Figure 5 below shows several instances of where cookstoves were found placed outdoors.

4.1.1. TEG cookstoves were used more outdoors than traditional cookstoves

When the distributed TEG cookstove had been used, it had been used by only two households exclusively inside the kitchen, and otherwise a mix between both indoors and outdoors or outdoors only.

Figure 5 shows three instances of clean cookstoves being used indoors, indicating that at least three of the households were using clean cookstoves, despite the criteria for receiving a TEG cookstove having been that a household did not possess clean cookstoves or have the means to buy gas for use with clean cookstoves.

All surveyed households had kitchens with doors. Four had holes in the wall for ventilation, one had a window and one had a chimney.

Figure 6 illustrates what the holes in the wall looked like in two different households with soot evident on the walls of the first.

4.2. Cooking habits and fuel-use

4.2.1. Three hobs

As table 2 above shows, three was the modal number of hobs in use.

Two-thirds of respondents prepared on average three meals per day, whereas one third prepared two meals per day—taking an average of 7.3 h per day. Table 2 shows the distribution of reported hours per day spent in the kitchen.

One respondent bought all their firewood. Eight respondents said that they collected all their firewood from the forest. The tenth household reported not using fuelwood any longer—they had used it only for the TEG cookstove, but now used gas and electricity exclusively.

4.2.2. Biomass for the TEG cookstoves

In terms of fuels used for the TEG cookstove, every household reported using wood. In addition, two reported using twigs one reported using charcoal and one each reported using cow dung and coconut shells, although more may have used the latter two since these were not offered options, but rather volunteered by two separate households themselves.

4.3. 5.3 TEG cookstove use, perceived impact on fuel efficiency, smoke output, and on health

4.3.1. Lack of use after two years

As table 3 below shows, two years after distribution, no respondent reported having used the TEG cookstove in the past month. Two respondents reported never having used the TEG cookstove, one respondent reported not using the TEG cookstove because it was broken and the remaining seven households reported not having used

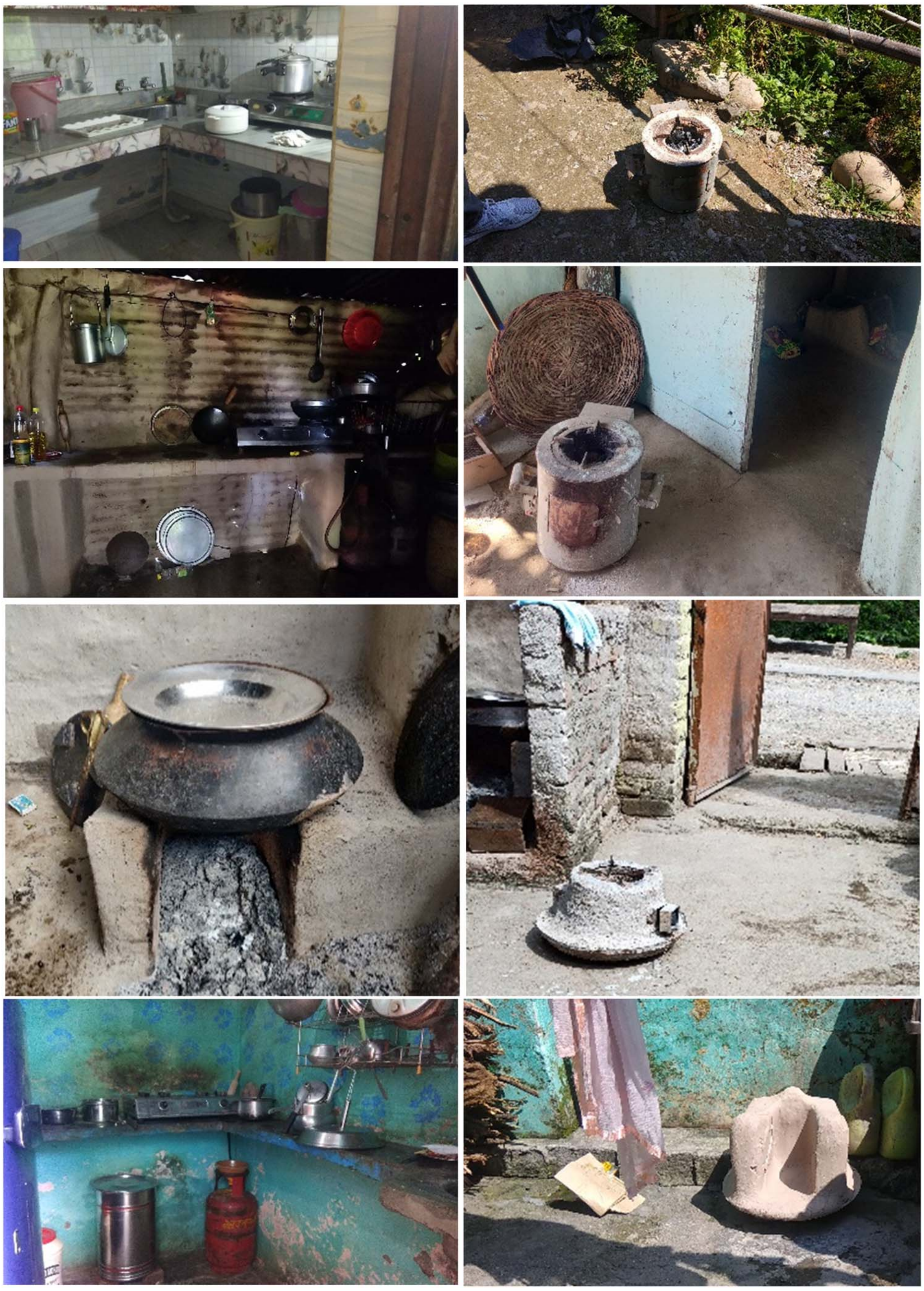

Figure 5. Cooking indoors (left column) and outdoors (right column)—each row is a different household. *Source: Authors' TEG cookstove survey, 2021.*

the TEG cookstove in over a month—two of these reported not having used it more than half a year. Two of those whom had used it said that they would use it in the winter for heating the house.

4.3.2. Had been used for cooking traditional dishes

When they had used the TEG cookstove, householders had used it primarily for slow cooking, which 7 respondents said it was good for, in contrast to no respondents who said it was good for cooking over a medium timescale of 5–30 min, and no respondents said it was good for quick cooking. When they had used the TEG cookstove, respondents had used it for cooking. Eight had used it for cooking vegetables and for *roti* (unleavened bread). When respondents were asked if they had any other unprompted things they liked about the TEG cookstove, four said that they liked the TEG cookstove for cooking roti. On the other hand, when asked if they had any unprompted things they disliked about the TEG cookstove, one respondent said that they did not like it for cooking roti because its flame went too high.

Figure 6. Holes in the wall for ventilation. *Source: Authors' TEG cookstove survey, 2021.*

Table 2. Survey results for cooking and fuel-use.

Cooking habits and fuel-use					
Cooking habits					
# stoves used	# responses	# meals prepared/day	# responses	# hours/day cooking	# responses
1	0	1	0	3–<6	2
2	2	2	2	6–<8	5
3	7	3	7	8–<10	2
4	1	4	1	10–12	1
Total	10	Total	10	Total	10
Fuel use					
Fuelwood	# responses	**Fuels used in TEG cookstove**	# responses		
Purchase 100%	1	Wood	10		
Forest - collect 100%	8	Twigs	3		
Total	9	Charcoal	1		
		Cow dung (written in)	1		
		Coconut shell (written in)	1		

Beyond vegetables and *roti*, six respondents had used the TEG cookstove for cooking *daal* (lentils), and it had also been used for making rice, tea and boiling milk. No respondents reported using the cookstove for cooking fish and red meat, but this may have been because these foods did not feature in the largely Hindu sample's diets.

4.3.3. Seldom used for non-cooking uses, electricity generation irrelevant

The TEG cookstove had not been widely used for non-cooking uses, and not at all for electricity. The extent to which respondents reported a change in use of electricity since receiving the TEG cookstoves was zero. No respondent reported that they thought that the electricity generated was of poor quality. All the respondents reported having grid electricity connections and no other backup source. No respondent thought that the TEG cookstove was good for heating at high temperatures.

4.3.4. Perceived to use less fuel

Seven of eight respondents thought that the TEG cookstove used less solid biomass. As a result, when asked what they thought was good about the TEG cookstove, three respondents highlighted that it reduced the amount of fuelwood required.

4.3.5. Perceived to emit a lot less smoke, but not confer health advantages

When they had used the TEG cookstove, eight of 10 respondents thought it decreased smoke in the kitchen and house by a lot, and the remaining two thought it decreased smoke by a little. In spite of this, no respondent perceived change in the health of the person responsible for cooking. Specifically, no changes were reported in phlegm, breathlessness or wheezing, or sore or itchy eyes. Interestingly, every respondent reported no coughing, no phlegm, and no breathlessness or wheezing either before receiving the TEG cookstove or at the time of being asked.

Table 3. Survey results for TEG cookstove adoption and perceptions.

TEG cookstove adoption and perceptions					
Adoption					
Last use of TEG cookstove	# responses	When used, uses - cooking	# responses	When used, uses - non-cooking	# responses
Used in last month	0	Vegetables	8	Making water safer to drink	1
Not in use - broken	1	Roti (unleavened bread)	8	Heating bath water	1
Used 1–6 months ago	4	Daal (lentils)	6	Providing household heat	1
Used >6 months ago	3	Rice	3	Providing light	1
Never used	2	Chai	3	Providing electricity to lights, mobile, radio, fan, TV	0
Total	10	Boiling milk (written in)	2		
		Chicken	1		
		Fish	0		
		Red meat	0		
Negative perceptions Complaints	# responses	Written in explanation/conclusion	# responses		
Inlet too small	3				
		Need to cut wood into small pieces (written in)	1		
		Time consuming (written in)	1		
Small stove (written in) - all excl. from inlet too small	3				
		Need to cut wood into small pieces (written in)	1		
		I don't like TEG cookstove (written in)	1		
Total	**6**				
Difficult to cook / make roti (written in)	1				
		Flame is high outside this stove (written in)	1		
I try to burn fire in this stove but I can't (written in)	1				
		I don't like TEG cookstove (written in)	1		
Total	**2**				
Broke down	3				
		Broken fan	1		
Repair or replacement of electronic part is difficult (written in)	1				
Not working properly - mutually excl. from 'broke down' option	1				
Total	**5**				

Table 3. (Continued.)

TEG cookstove adoption and perceptions					
Adoption					
Last use of TEG cookstove	# responses	When used, uses - cooking	# responses	When used, uses - non-cooking	# responses
What to improve	# responses	Change time spent cooking	# responses		
Enlarge inlet (/10)	6	Reduced by a lot	0		
Increase size for larger dishes (/10)	1	Reduced by a little	0		
Bigger (written in) - all excl. from increase size for larger dishes	4	Same	6		
Decrease height (written in)	1	Increased by a lot	0		
Larger fan	1	Increased by a lot	3		
		Total	9		
		Good for (lack of positive responses)	# responses		
		Medium cooking (5–30 min) (/9)	0		
		Quick boiling (/10)	0		
		Medium temperature (/10)	1		
		High temperature (/9)	0		
Positive perceptions					
Change in smoke observed	# responses	Change in solid biomass used	# responses	Good for (several responses)	# responses
Decreases by a lot	8	TEG uses a lot more	0	slow cooking (/10)	7
Decreases by a little	2	TEG uses a little more	0	low temperature (/10)	4
Stays the same	0	TEG uses same	1	Likes to make roti in TEG (written in)	4
Increases by a little	0	TEG uses a little less	7	Uses less firewood (written in)	3
Increases by a lot	0	TEG uses a lot less	0		
Total	10	Total	8		
Electricity use					
When last used TEG for electricity	# responses	Source of electricity	# responses	Electricity use change	# responses
Never	10	Grid	10	Decreased by a lot	0
		Solar home system	0	Decreased by a little	0
		Generator	0	Stayed the same	10
		Vehicle battery	0	Increased by a little	0
		Outside the house	0	Increased by a lot	0

Table 3. (Continued.)

TEG cookstove adoption and perceptions					
Adoption					
Last use of TEG cookstove	# responses	When used, uses - cooking	# responses	When used, uses - non-cooking	# responses
		Friend/family's	0	Total	10
Health - indicators and perceptions					
Non-existent complaints	# responses				
Felt more dangerous	0				
Reported coughing	# responses	Reported phlegm	# responses	Reported wheezing	# responses
Never	10	Never	10	Never	10
A little	0	A little	0	A little	0
Sometimes	0	Sometimes	0	Sometimes	0
Often	0	Often	0	Often	0
All the time	0	All the time	0	All the time	0
Total	10	Total	10	Total	10
Reported change in coughing	# responses	Reported change in phlegm	# responses	Reported change in wheezing	# responses
Decreased by a lot	0	Decreased by a lot	0	Decreased by a lot	0
Decreased a little	0	Decreased a little	0	Decreased a little	0
No	0	No	0	No	0
Increased a little	0	Increased a little	0	Increased a little	0
Increased by a lot	0	Increased by a lot	0	Increased by a lot	0
Not applicable	10	Not applicable	10	Not applicable	10
Total	10	Total	10	Total	10

Figure 7. Home-adaptation of TEG cookstove. *Source: Authors' TEG cookstove survey, 2021.*

4.3.6. Small inlet a barrier to use

Asked what they did not like about the TEG cookstove, three respondents said that the inlet for biomass was too small and three more said that the TEG cookstove was too small. Six respondents said that enlarging the inlet would improve the TEG cookstove. Two respondents explained further that the inlet required cutting fuelwood into small pieces, and one of them explained that it made for time consuming cooking. Indeed, three respondents reported that using the TEG cookstove increased the time spent cooking by a lot. All other suggestions for improvement of the TEG cookstove centred around size: five said that they wanted an increased size for larger dishes or just larger in general, and one suggested a larger fan. Figure 7 shows one modified TEG cookstove with the electronic component removed to enlarge it and make it easier to cook roti.

4.3.7. Lifespan limitation

Two years after distribution, five households (half the sample) reported that the TEG cookstoves had either broken down, were in need of repair or replacement of an electronic part, or were not working properly.

5. Discussion

This was the first time an adoption study of TEG cookstoves had been conducted over a time horizon exceeding six months, as previous studies had been conducted over much shorter time horizons—ranging from two weeks to 6 months (O'Shaughnessy *et al* 2014, O'Shaughnessy *et al* 2015, Wilson *et al* 2018).

Our survey showed lack of use of TEG cookstoves two years after distribution. Their distribution under the Unnat Bharat Abhiyan programme did not therefore continue to contribute to the Government of India's objective of helping villagers meet their cooking needs with local resources in a less harmful manner to the environment or to villagers' health. (Ministry of Human Resource Development, IIT Delhi and Unnat Bharat Abhiyaan 2018). Because the TEG cookstoves were not used after two years, they did not effectively promote good health and well-being (SDG 3) nor affordable and clean energy (SDG 7). By not being used, they did not reduce the time women spent collecting fuelwood and reducing fuelwood collected, and so did not provide women more time to pursue decent work and economic growth had they wanted to (SDG 8), did not reduce gender inequality (SDG 10), and did not reduce greenhouse gas emissions (SDG 13), nor reduce environmental degradation (SDG 15).

To understand why the decentralised, eco-friendly technology did not continue to be used after two years, we interpret some of the results using the COM-B framework, and then use the BCW framework to understand how barriers to adoption can be surmounted.

5.1. TEG cookstove barriers to adoption—application of the COM-B framework

We observed many barriers to use. In figure 8 we suggest an approximate waterfall model of barriers between no adoption at all and ongoing use, to account for the multiple factors that contribute to decision-making. The waterfall model indicates whether barriers are Opportunity, Capability or Motivation barriers from the COM-B framework.

As the TEG cookstoves were distributed for free or at a subsidised rate used free solid biomass, TEG cookstoves did not encounter the Physical Opportunity barriers to adoption of being unaffordable to purchase

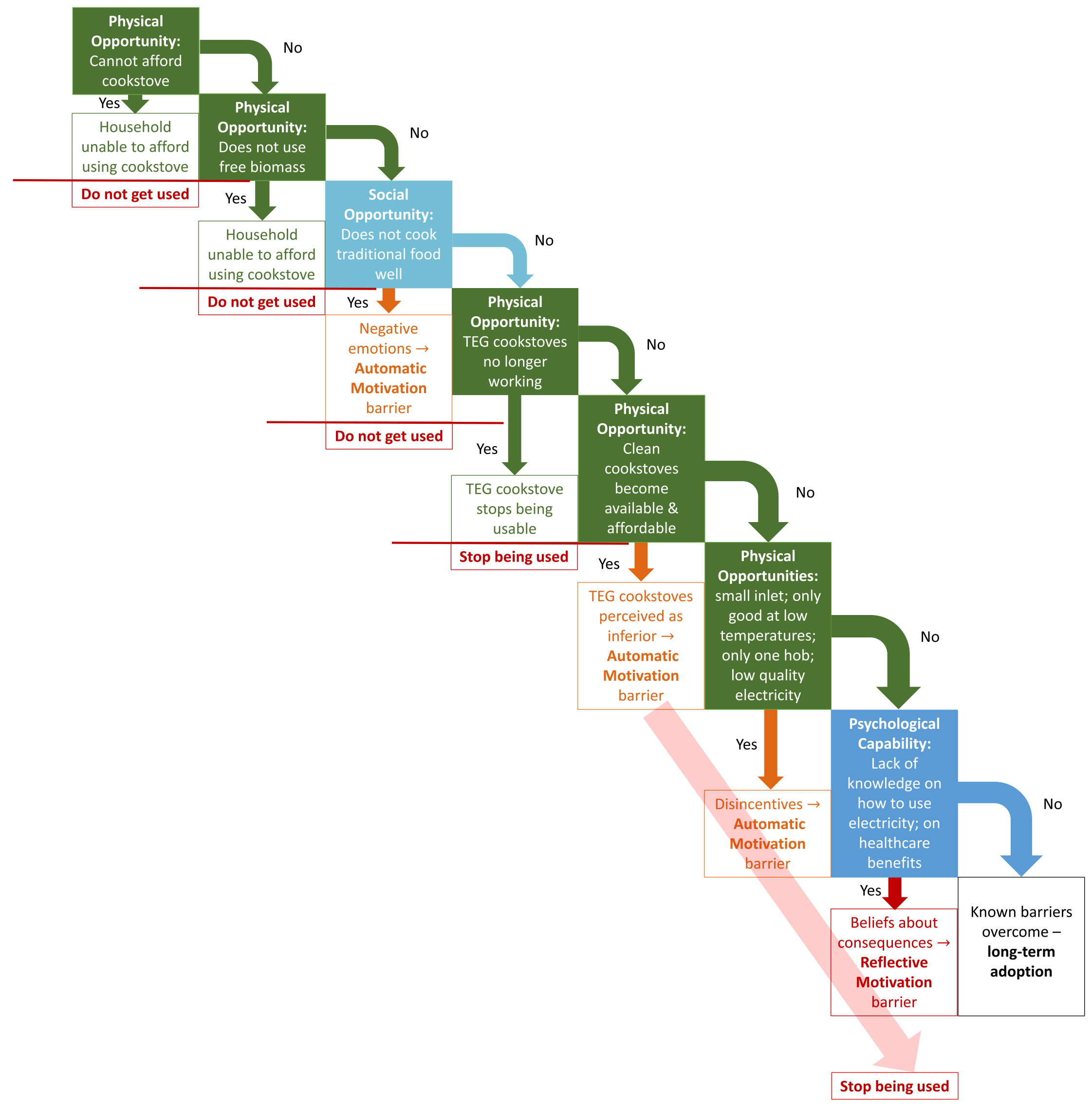

Figure 8. Barriers to use of TEG cookstoves.

that clean cookstoves have, as observed by Gould and Urpelainen (2018) and by Perros *et al* (2022). The TEG cookstoves were adopted for a while and were generally appreciated for cooking some traditional foods, so did not succumb to the social opportunity barrier to adoption that TEG cookstoves tested in India by Wilson *et al* did (Wilson *et al* 2018).

In a few cases, users stopped physically being able to use TEG cookstoves because they lacked access to maintenance and repairs, and the TEG cookstoves stopped working, representing a Physical Opportunity barrier. This observation echoes Hanna, Duflo and Greenstone's finding that lack of maintenance investments leads to a decline in use of improved cookstoves (2016), as well as Perros *et al* (2022) finding that this was a major Physical Opportunity driver for clean and improved cookstoves.

In a few cases, clean cookstoves started displacing TEG cookstoves out of cookstove stacking when households attained clean cookstoves for use indoors, and attained the ability to buy clean cooking fuel. (Users had been trained not to use the TEG cookstoves indoors.) This is not a problem if households start using clean cookstoves only, or at the least if the reduced use of TEG cookstoves does not increase the use of traditional cookstoves, especially indoors. It is a problem if the reduced use of TEG cookstoves increases the use of traditional cookstoves.

Physical characteristics of the TEG cookstoves represented Physical Opportunity barriers that contributed to their disuse: their small inlets for biomass; their limited versatility in heating quickly and at high temperatures; their single hob (in contrast with the multi-stove clean cookstoves that we see in figure 5). Their tier 0 electricity generated may also have been insufficient to motivate the TEG cookstoves to use the electricity feature.

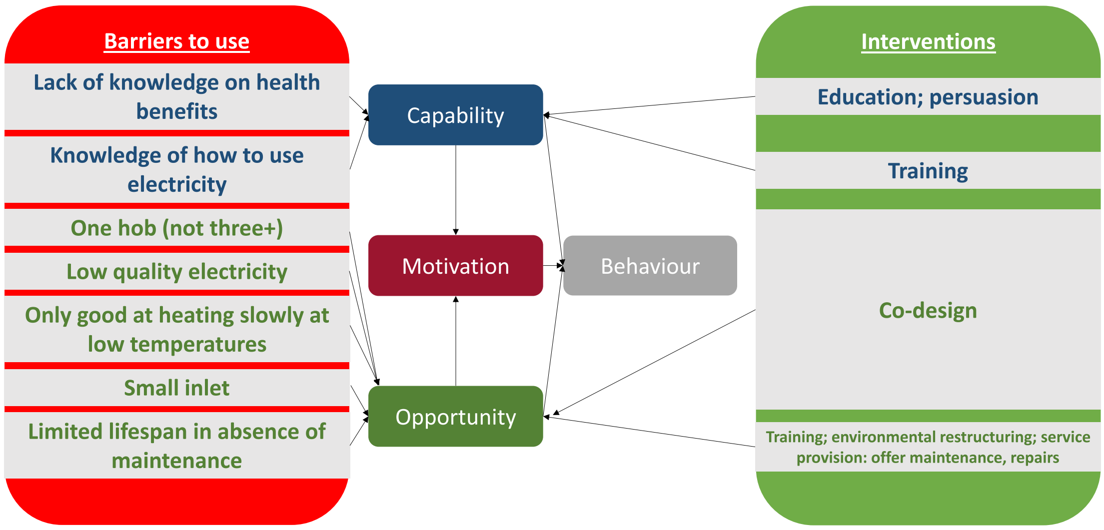

Figure 9. Barriers to adoption of TEG cookstoves, and possible solutions to surmounting those barriers.

Coupled with these Physical Opportunity barriers were Psychological Capability barriers of their users. One of these Psychological Capability barriers was the apparent lack of knowledge of the healthcare benefits of using less polluting cookstoves. Contrasting some of the reports of good health are photographs shown in figures 5 and 6 which depict sooty walls (not all of them do). Where the householders are using indoor traditional cookstoves with biomass, there is likely a knowledge capability barrier about the impact that indoor cooking with biomass is having on the householders' health.

Another possible Psychological Capability barrier is lack of knowledge of how to use the TEG cookstoves' USB ports, which represented a new physical opportunity that did not end up inducing use. Another possible and not mutually exclusive explanation for not using the electricity available is an Automatic Motivational barrier given the low power of electricity produced, which also poses a Physical Opportunity barrier. The IIT Delhi field team assessed the TEG cookstove to fall under tier 0 of the ESMAP multi-tier framework for measuring access to electricity, estimating that the cookstove would deliver fewer than 12Wh of electricity per day. If the villagers did not experience power outages in the months preceding the survey, they would not have been motivated to use alternatives to their grid connections (indeed no respondent reported having any backup power generation capability). This contrasts with the finding of Wilson *et al* (2018) that users in the Indian state of Odisha valued the USB charging port. The difference between the two studies is that in their case, recipients of the TEG cookstove did not have access to electricity.

The coupling of these Physical Opportunity and Psychological Capability barriers resulted in the use of alternative cookstoves, and eventually became a habitual and automatic ignoring of the TEG cookstoves so that by the end of two years, no users were using TEG cookstoves.

5.2. Surmounting barriers to adoption

Having analysed the factors leading to a failure to adopt or to continue use of the TEG cookstoves, the Behaviour Change Wheel framework indicates how barriers to adoption can be overcome, as illustrated in figure 9. To prevent abandonment of TEG cookstoves because they no longer work, there needs to be service provision of maintenance, or at the least provision of repair work. To this end, in a commercial venture, the phone numbers of staff could be provided. Training could also be provided to users to enable them to maintain their TEG cookstoves.

The increased affordability of clean cooking is not a problem to address unless the reduced use of TEG cookstove use somehow results in the increased use of traditional cookstoves. This is an area to be investigated further.

The physical deficiencies of the TEG cookstove identified in our survey (small inlet for fuel, only good at slow cooking at low temperatures, low power electricity and only one stove) should be addressed, and, to the extent that it makes sense, the end-users should be involved in the co-design.

Training should be offered periodically together with maintenance checks. This may increase the use of charging up electrical devices, although this could lead to increased emissions of air pollutants. Education should be provided to address the lack of knowledge about the medical benefits of less polluting cookstoves; particularly to those using traditional cookstoves indoors and with sooty walls. Complementing this education could be messaging about the visible and more immediate effects of less sooty walls.

5.3. Limitations

Initial plans for the deployment of additional and modified TEG cookstoves that may have seen greater adoption to the 15 that were initially distributed in the village cluster of Gaindikhata between June and August 2019 were prevented by the COVID19 pandemic. Nonetheless, we were able to complete possibly the first small-scale longitudinal survey of TEG cookstove adoption and perceptions.

6. Conclusion

The Government of India has supported the development and promotion of efficient and cost-effective improved biomass cookstoves through such programmes as Unnat Bharat Abhiyaan which funded the distribution of TEG cookstoves used in this study. It did so with the intent of targeting better environmental and health outcomes for villagers using locally available resources. Beyond meeting these national goals, its continued support of TEG cookstoves could also help address SDGs 3, 7, 8, 10, 13 and 15. Once on the market, such support could include complementing vendors' efforts by providing health education on indoor cooking and cooking with traditional cookstoves. To reduce the unit costs of importing TEG components, it could procure in bulk TEG cookstoves assembled domestically and waive import duties on TEG components, at least until domestic suppliers can manufacture them. To the extent that there is still a gap between the cost of production and affordability for target users who cannot afford clean cooking solutions, it could subsidise that gap.

The first issues to address, however, as the focus of our study emphasises, is the TEG cookstove's design and aftercare. The first longitudinal study of the adoption and perceptions of TEG cookstoves shows that after two years, distributed TEG cookstoves were no longer in use. This is consistent with over three decades of many unsuccessful interventions to promote the adoption of improved cooking stoves. The Capability, Opportunity, Motivation-Behaviour (COM-B) framework helped understand barriers for adoption of TEG cookstoves and the Behaviour-Change Wheel (BCW) framework helped develop recommendations to improve adoption.

Physical Opportunity barriers to continued use for the TEG cookstoves were their limited lifespans in the absence of maintenance; their small inlets for fuelwood; their provision of only one hob; their low power of electricity production; and their low cooking power. Users' capability barriers to TEG cookstoves' use was their lack of knowledge of their health benefits relative to traditional cookstoves; and perhaps lack of knowledge of how to use their USB charging ports. We recommend engineers involve users in the co-design of the TEG cookstove to better design fuel inlets and other components of the stove. More broadly, a user-centric approach should be used where engineers co-design solutions with end-users from the outset. Once on the market, we would recommend that vendors offer users training on the use of the cookstove and USB charging port, emphasise the visual benefits (less soot) of using TEG cookstoves over traditional cookstoves, and provide the maintenance required to ensure longevity of the cookstoves.

The study shows that providing technologies by itself is not enough to aid clean energy transitions, especially for clean cooking. There needs to be co-development and community engagement embedded in the process of technology development.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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