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The use and impacts of an ethanol cooking fuel promotion pilot in Dar es Salaam

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ABSTRACT

Ensuring access to affordable and clean energy resources (as articulated in Sustainable Development Goal (SDG) 7) is critical to achieving a range of human development outcomes. Numerous studies have examined how clean cooking technology can, under the right circumstances, reduce household air pollution and shift household time use. Yet, empirical research on the adoption and impacts of bioethanol, an emerging clean cooking fuel that is frequently promoted in policy dialogues, remains limited and largely descriptive. Thus, this paper evaluates the effects of a large-scale, UNIDO/GEF-sponsored ethanol promotion program implemented in Dar es Salaam, Tanzania. To mitigate against bias from non-random selection into ethanol stove ownership and confounding by observable factors that may influence the outcomes of ethanol stove adoption, we apply multiple regression and matching methods to analyze survey data collected from 844 households. We document increases in cooking time with ethanol fuel and primary use of ethanol stoves, indicating that this technology was taken up by targeted households. Yet, no clear health improvements or net time savings result among these households. This is likely due to the continued use of charcoal stoves and insufficiently robust stoves, which dampen cooking time savings and air pollution reductions, and a weak ethanol fuel supply chain to convenient retail outlets, with implications for fuel collection time. Improvement in technology and program design and implementation, focusing on user experiences and convenience aspects, is necessary to achieve better outcomes and deliver tangible economic benefits to households.

Introduction

Worldwide, as of 2024, over 2 billion people still cooked using solid fuels like wood, crop waste, charcoal, coal and dung as well as kerosene on open fires and inefficient stoves. The urgency for intervention is especially pronounced in sub-Saharan Africa, where hundreds of millions of people lack access to clean cooking, and where population growth continues to outpace the growth in availability of these options (WHO, 2022). In Tanzania, the location of this study, the majority of residential energy consumption comes from biofuels and waste; 90 % of households used either charcoal or firewood as their main cooking fuel as recently as 2017 (Doggart et al., 2020). Dar es Salaam alone accounts for nearly 50 % of national charcoal consumption (UNIDO, 2023). Indeed, urban charcoal use reduction, especially in the capital, is a policy goal that is receiving increasing attention in the country owing to climate, deforestation and health concerns (MNRT, 2022; URT, 2015), despite significant controversy and little success to date (Mabele, 2020).

Policy pronouncements and initiatives to discourage charcoal use in Tanzania are motivated by several factors. First, the use of biomass fuels such as charcoal is linked to significant adverse health effects caused by household air pollution (HAP) – fine particulate matter and other pollutant emissions generated during these fuels' combustion (HEI & IHME, 2024). HAP is a major health risk globally: As recently as 2021, approximately 3.6 billion individuals, or nearly half of the world's

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population, were exposed to dangerous levels of it (HEI, 2018). Annually, about 3 million people are estimated to die prematurely from illnesses associated with exposure to cooking-related HAP (WHO, 2022). The problem is especially severe in a group of approximately 24 African nations, including Tanzania, where >90 % of households use solid fuels as their primary cooking energy source, 98 % are exposed to HAP, and where HAP is the leading environmental risk factor for morbidity and mortality (Forouzanfar et al., 2015; State of Global Air, 2023). Owing to population growth, the number of people exposed to HAP in Tanzania has even been increasing over time (World Bank, 2023).[1]

Second, fuelwood harvesting for cooking degrades the environment, contributing to deforestation, forest degradation and depletion of carbon stocks, and biodiversity loss. Traditional wood fuel use in Africa significantly contributes to forest degradation and accelerates climate warming (Quinn et al., 2018), with solid fuels combustion globally contributing approximately 2 % of global greenhouse gas emissions (Nyambane et al., 2020). The Tanzania government views the annual forest loss of about 372,000 ha (1 % per year) as a serious environmental challenge (FAO, 2015), and efforts to move towards more sustainable charcoal production have thus far had only limited success (Mabele, 2020).

Ethanol is a clean-burning fuel that has the potential to reduce HAP exposure, improve health, and advance household cooking efficiency as an alternative biofuel to charcoal and wood, while also avoiding fossil fuels such as kerosene or LPG (Mudombi et al., 2018; Olopade et al., 2017). According to a recent systematic review, average reductions of 83 % in kitchen $PM_{2.5}$ (fine particulate matter) and 82 % in CO (carbon monoxide) were observed following the introduction of ethanol stoves in small-scale assessments conducted in low- and middle-income countries (Pope et al., 2017). Moreover, ethanol stoves are purported to be user-friendly and convenient, requiring less effort for fire preparation and post-cooking cleaning compared to charcoal and fuelwood stoves (Practical Action Consulting, 2011). The market penetration of this fuel remains low (Putti et al., 2015), though, owing to a complex set of barriers including the high cost of ethanol from legacy sugar factory distilleries, lack of public awareness, and inadequate infrastructure for fuel distribution (Schlag & Zuzarte, 2008). Meanwhile, relatively little is known about users' perceptions of ethanol cookstoves, who adopts these technologies, and how cooking behavior changes and what broader health and socio-economic impacts result, when these are adopted (Lambe et al., 2015). Most prior work has only examined emissions reductions, under controlled testing conditions (Pennise et al., 2009), or broader impacts in small-scale observational pilot studies with convenience samples (Osiolo et al., 2023), without adequate control for selection or confounding factors (as in, e.g., Armstrong et al., 2023).

To help address these gaps, we evaluate the impacts of the "Promotion of Ethanol as Alternative Clean Fuel for Cooking in the United Republic of Tanzania" program on ethanol-adopting households in Dar es Salaam. The project, sponsored by the United Nations Industrial Development Organization (UNIDO) and the Global Environment Facility (GEF) (UNIDO, 2018, 2024), aimed to 1) train local stakeholders to manufacture stoves and produce and distribute fuel grade ethanol; 2) establish a policy framework in Tanzania for promoting ethanol-based cooking; and 3) roll out an ethanol cooking promotion program at scale. Its long-term goal was to stimulate investment in energy efficient ethanol cooking systems and ethanol production. The program was approved in 2017, initiated in Dar es Salaam in 2018, and its two phases were originally planned to be completed by October 2024 (UNIDO, 2024). Project planning documents argued that: "the proposed intervention will address the key barriers in switching to ethanol-based clean cooking practices and facilitate the distribution of ethanol clean cooking fuel and technology to 500,000 households in Dar es Salaam" (UNIDO, 2024). Those key barriers included, among others, lack of sufficient incentives to manufacturers and households to engage with this new technology; a non-existent local supply chain and of suppliers and distributors of both stoves and fuel (including marketing); and lack of demand for ethanol cooking, due to non-awareness among consumers of the possibility of cooking with that fuel (UNIDO, 2024).

In line with the above, a key feature of this program is selling ethanol stoves to households at a time-limited subsidized (incentivized) rate. The subsidized starter package consisted of one single-burner stove plus two liters of ethanol for 50,000 TZS (about US $22). The total implied subsidy for consumers thus amounted to $16; an additional $8 was allocated to offset the distributor's marketing costs (UNIDO, 2024). Consumers Choice Limited (CCL), a wholesale company with experience in buying and selling bioethanol, was competitively selected to be the distributor for the rollout and given a target to distribute cookstoves to households in 20 selected wards in Dar es Salaam (UNIDO, 2024). The ethanol fuel was sourced from a sugar factory distillery in Tanzania, bottled by CCL, and sold to communities at about a dollar per liter, reflecting the full cost of fuel production and distribution. This pricing is more or less competitive with charcoal, which is currently the cooking fuel of choice among lower and middle-class people in Dar es Salaam. As of December 2024, CCL had sold over 20,000 ethanol cookstoves, up from 10,000 in late 2022 (UNIDO, 2024).

We focus our evaluation of the causal impacts of this investment program on household use of the ethanol cooking stoves and fuel, and impacts on health, energy expenditures and time use. Our contribution is to provide some of the first rigorous estimates of household impacts from this nascent cooking industry, in a representative sample of consumers, and to point to challenges that should receive attention from designers of similar future efforts. A companion paper, Benka-Coker et al. (2025), examines infrastructure, implementation and policy details in detail, as well as stakeholder perceptions within the ethanol cooking supply and demand ecosystem, using mixed methods and applying an implementation science framework. Together, these studies provide rich insights that can inform future efforts to scale up ethanol as a cooking fuel, including how policy incentives can be structured to better support clean cooking energy transitions in similar urban settings.

Background and literature review

Clean cooking initiatives have gained increasing attention, driven by concerns about health, the environment, and sustainable development. This section reviews prominent recent impact evaluations of clean cooking promotion efforts, with particular emphasis on those examining ethanol cooking promotion.

Comprehensive impact evaluations of clean fuel transitions are relatively scarce in the literature. However, given recent momentum in several countries, especially in urban areas (Das et al., 2024; Wei & Lin, 2024), evidence on the ingredients of effective interventions is beginning to accumulate (Bensch & Peters, 2020; Pattanayak et al., 2019). Many studies have focused on liquefied petroleum gas (LPG) fuel, the most widely used clean cooking fuel in many countries (Stoner et al., 2021). Interventions to encourage the adoption of LPG include the provision of equipment to households for free, and use of financial incentives such as purchase subsidies and taxes (Adjei-Mantey et al., 2021). Importantly, countries such as Indonesia, India, Ecuador, Ghana, Brazil, and Peru have pursued and achieved accelerated household cooking transitions largely by deploying LPG subsidies that enhance affordability on a broad scale (Das et al., 2022; Lucon et al., 2004).

For instance, Lucon et al. (2004) analyzed the impacts of LPG subsidies that were in place in Brazil from 1950 through 2001, and attributed the dominance of that cooking fuel (with use by over 150 million people or 98 % of households) to such supports. Andadari et al. (2014) evaluated the impact of a large government program to subsidize LPG in

[1] According to the most recent Census from 2022, the population increased by 17 million people between 2010 and 2022. In 2019, when the increase relative to 2010 was 15 million, 12 million of those additional people were primarily using solid fuels for cooking.

Indonesia in 2007 and found that this program was similarly highly effective in causing a large-scale shift from kerosene to LPG; Verma and Imelda (2023) relatedly showed that this transition led to health and empowerment improvements for women. In Ghana, the Rural LPG Promotion Program started in 2013; it also stimulated higher LPG usage, increasing both the probability that households would choose LPG as a primary cooking fuel and the quantity used (Adjei-Mantey et al., 2021). Calzada and Sanz (2018) and Pollard et al. (2018) studied Peru's LPG substitution program, created in 2012, and showed that beneficiaries receiving monthly discount vouchers used LPG significantly more than non-beneficiaries. Finally, Kimemia and Annegarn (2016) assessed the 2006 LPG intervention program in Atteridgeville, South Africa and found that the program successfully encouraged LPG adoption, making it the second most favored cooking fuel after electricity.

A frequent concern of policymakers and consumers of LPG is over how to ensure supply and delivery infrastructure and address safety concerns (Puzzolo et al., 2019). Moreover, LPG presents sustainability and emissions-related challenges amid the growing urgency of decarbonization and environment- or health-harming pollution. An experimental study of the effect of LPG on ozone formation in Mexico found that leakage and incomplete combustion of LPG contributed significantly to excessive ozone profiles (Luis et al., 2003). Additionally, a biomass-to-LPG intervention trial in Peru revealed that concentrations of health-harming NO_2 in LPG-using households exceeded annual and hourly guidelines despite reductions relative to biomass fuel use, with large concentration peaks observed in kitchen area during common cooking time (Kephart et al., 2021).

Use of clean fuels other than LPG (e.g., biogas, ethanol, and electric cooking) theoretically alleviates several of these concerns, but careful field assessments are limited, and adoption by households has historically been much lower. For electric cooking, climate implications depend on the source of electricity generation, but a more significant impediment has been a lack of reliable supply in many low-income countries (Parikh et al., 2020). Ethanol and biogas are classified as clean, renewable fuels that tend to produce low emissions, and concerns related to environmental sustainability and negative implications for food security – given relatively modest cooking fuel needs relative to other potential use of ethanol (e.g., as a transportation fuel) – have largely been resolved (Osiolo et al., 2023). For example, lab testing (e.g., under the U.S. Environmental Protection Agency (EPA)'s cookstove testing program) indicates that ethanol burners contribute negligibly to background levels of CH4 (methane) and NOx (nitrogen oxides) (Jetter et al., 2015), while field evaluations suggest that ethanol fuel interventions reduce PM more than other clean fuels (Pope et al., 2017). The latter results should be viewed cautiously, however, as they may reflect differences in background (or ambient pollution) concentrations across studies, especially when considering electric cooking.

Additional evaluation work is sorely needed to inform the design and improvement of ethanol promotion interventions (Ozier et al., 2018), but the challenge thus far has been to find interventions that have effectively scaled up (Osiolo et al., 2023). Charron et al. (2011) evaluated a pilot effort in Madagascar and found that ethanol can be a compelling alternative to solid fuels, given high levels of user acceptance of the stove and fuel (87 % of that study's ethanol stove-owning households reported it as their primary cooking device), and the sharp reductions in household concentrations of $PM_{2.5}$ and CO achieved (Charron et al., 2011), plus decreased symptoms of eye irritation, headaches, and burns in mothers and children. Ozier et al. (2018) examined the acceptability of blended ethanol/methanol fuel and willingness to pay for a "CleanCook" ethanol stove promoted during a pilot distribution and sales program in Lagos, Nigeria. Sales data indicated sustained usage of ethanol stoves. However, in both this and the Madagascar study, many households emphasized a need to maintain use of a secondary stove, due to difficulties in obtaining or affording the fuel and limitations in its ability to cook sufficient quantities of food and all food types. The health effects of CleanCook stove use were further studied using a randomized control trial in Nigeria, which found suggestive evidence for reduced cardiovascular health risks (Olopade et al., 2017).

Other pilot ethanol evaluations have taken place in humanitarian settings, such as among low-income populations in refugee camps in Ethiopia, including the Shimelba, Bonga, Kebribeyah, Tsore and Sherkole Camps, as well as with low income households in Addis Ababa (Benka-Coker et al., 2018; G/Egziabher et al., 2006; Gaia Association, 2019; Murren, 2006; Pennise et al., 2009). In Addis Ababa, most users were satisfied with the CleanCook stoves in terms of the ease of use, fuel consumption, safety, etc., and the ethanol-fueled stove was clearly more fuel efficient and safer than kerosene (Murren, 2006). Pennise et al. (2009) complemented these findings by demonstrating significant reductions in $PM_{2.5}$ and CO concentrations in households' cooking areas in that setting and in the Bonga and Kebribeyah Refugee Camps. In the study conducted in the Shimelba Camp, meanwhile, refugee families using the CleanCook stove spent less money on fuelwood, time gathering fuelwood, and reported less coughing and eye irritation (G/Egziabher et al., 2006).

As highlighted above, evaluations of larger scale ethanol-promotion efforts are rare, because the business models for this intervention remain difficult. One notable example is Project Gaia's assessment of the adoption and potential benefits of ethanol fuel and stoves among households in Zanzibar, Tanzania (Tadele et al., 2015). That study found that ethanol fuel used with the CleanCook stove effectively reduced HAP in households where it was the only stove used. Firewood collection burdens were also reduced, mitigating deforestation and decreasing reliance on dirty fuels, and cooking times were also lowered (Tadele et al., 2015). A second notable study examined user perceptions during a large ethanol stove and fuel promotion program initiated by the private company CleanStar, which distributed approximately 30,000 ethanol stoves in the greater Maputo area, starting in 2012 (Mudombi et al., 2018). Implementation there proved difficult: Those adopting ethanol cooking perceived the fuel to be expensive, and many discontinued its use during or after the promotion period as a result of cost, low fuel quality and poor stove design. More recently, Koko Networks has succeeded in an innovative commercialization endeavor for ethanol cooking that spans much of Kenya (Osiolo et al., 2023). Yet thus far, none of those scaled-up efforts have been examined using careful empirical methods that aim to measure causal impacts, using plausible control groups of similar non-users and controlling for confounding factors that may also affect the outcomes of interest. This is likely because of the resource needs, in time and money, of such work.

Methods

Based on the review of evidence presented above, additional assessments and evaluations of ethanol stove and fuel distribution programs outside of pilot settings are needed. Thus, we aim to evaluate a large-scale ethanol stove program, focusing on a comprehensive set of environmental, economic, and health-related impacts. We hypothesize that the ethanol promotion program will result in households adopting this technology, though we also anticipate a persistence of cooking technology stacking, in line with previous findings in the literature (Masera et al., 2000), and only muted health and socio-economic impacts in the short term for a program of this size. We also note here that the evaluation was paired with implementation science research to provide rich qualitative documentation of strategies employed in this unique program roll-out, which can inform future ethanol and other clean fuel scale-up efforts around the world (Benka-Coker et al., 2025).

Intervention

The UNIDO/GEF-sponsored bioethanol cookstove/fuel roll-out program was conceived as a multi-phase intervention beginning with an initial "proof of concept" phase (phase 1), which is the subject of our evaluation. In phase 1, originally planned to span 18 months starting at the end of 2019, UNIDO, the government, and financing partners (led by the Tanzania Investment Bank (TIB)) worked to first select a stove and fuel distribution company (Consumers Choice Limited (CCL)) via a competitive bidding process. CCL was tasked with developing a geographically limited marketing approach and localized supply chain for direct fuel provision to households or via local shops, starting in early 2020. This micro-targeting was deemed important to assure that CCL could maintain an uninterrupted supply of fuel in its assigned areas, and encourage CCL to focus on marketing, contact with consumers, and building a consumer-friendly supply chain for fuel delivery. Phase 1 was ultimately extended until the end of 2022 owing to COVID-19 related disruptions that adversely affected implementation timelines in 2020 and 2021. In phase 2, the idea was to then award similar contracts to new vendors who would work in their own areas of Dar es Salaam, leading to multiple distributors operating in the city, and setting the stage for healthy competition in the marketplace.

Initial customer adoption of the new stove and fuel – a “starter pack of one stove and two bottles of fuel – was supported by a small consumer subsidy, delivered using a results-based financing (RBF) mechanism aimed at enhancing affordability. Thereafter, fuel was sold at a price set by the distributor. CCL recuperated the cost of the subsidy by billing the government agency in charge of project finances, the TIB Bank, which used third-party verification to validate sales.

Sample design

Our sampling approach was developed to accommodate the constraints of the program intervention design, which were specified independent of researcher involvement. Thus, experimental or prospective quasi-experimental evaluation methods using panel data (e.g., difference-in-differences) were ruled out. Instead, we exploit the geographic targeting of the intervention, coupled with an approach that seeks to maximize the comparability of treated (registered CCL customers) and control (non-customers is untargeted wards) households.[2] Specifically, we drew a random sample of households from CCL's customer database, which tracked all households initially purchasing a stove in the target zones. Based on survey budget and statistical power considerations, we sought to enroll about 800 households (roughly evenly split into two groups: treatment and comparison).[3] Supervisors contacted a random sample of customers using phone numbers as well as address information, and households found to be living outside of the intervention's target areas were excluded and replaced with the next randomly selected household on the list.[4] In total, anticipating that matching to find suitable comparisons for some customer households would be difficult and would reduce sample size, we enrolled 483 consenting treatment households, and surveys with these respondents were completed in May–July 2022.[5]

To construct a comparable non-ethanol control group, we leveraged a representative prior household cooking energy use survey with 1000 households in Dar es Salaam, conducted in January–February 2020. That survey, funded by the World Bank and the Swedish International Development Cooperation Agency (Sida), had been administered by the same University of Dar es Salaam research team just before the onset of the global COVID-19 pandemic and the subsequent lockdowns in the city. Using the data collected in that survey, we drew a sample of households that was matched, using propensity score matching (PSM), to treatment sample observations on pre-intervention primary stove use (LPG or charcoal), fuel expenditure, reported hours of daily cooking time, and a set of demographic and socio-economic characteristics (household size, gender and age of household head, education of household head, income, a wealth index constructed from household asset ownership, distance to the nearest paved road and to the nearest market, and house construction materials).[6] After excluding households outside the common support region, and those who could not be recontacted in 2022, the final control sample comprised 361 households. Control surveys were completed in August–September 2022, bringing the total sample to 844.

The use of PSM for *ex-ante* sample construction has been used in various prior evaluations to increase the internal validity of causal estimates (Jeuland et al., 2021; King et al., 2007). However, there are several notable limitations – potential confounding by unobservables or time-varying factors, reduced generalizability of findings due to non-representativeness of the final analytical sample – to this approach, which inform the eventual econometric strategy we apply and describe below.

Survey instrument and variables of interest

The post-intervention survey that was administered to study households contained self-reported information on stove use, fuel consumption and expenditure, cooking time, and health and socio-economic indicators. We estimate the impact of the ethanol program on the following outcome indicators (dependent variables): primary usage of the ethanol stove, daily usage of ethanol stove and other stoves, frequency of using ethanol stove and other stoves, household expenditure on fuel, time spent cooking, time expenses for fuel collection, household total expenditure on illness treatment, and the health condition of the primary cook. We also investigate perceptions of ethanol fuel among ethanol user households. We acknowledge the limitations of reliance on self-reported data, but research budget constraints precluded validation using objective measurements; as such, results should be interpreted holistically, with inconsistencies across outcomes possibly arising from reporting bias.

Statistical methods

To analyze the impact of the ethanol program, we employ a combination of multiple regression and a second round of *ex post* PSM. Though neither approach can eliminate problems arising from selection on unobservables, both techniques reduce the threat of bias from confounding factors – regression via statistical control, and PSM by ensuring that treatment-control comparisons are not biased by selection on matching variables – and enhance the reliability of impact estimates. The first stage of PSM, which addresses selection into ethanol cooking fuel use based on observable factors, also provides insight on the household-level variables that influence bioethanol stove adoption and use.

Multiple regression

We utilize multiple linear regression and logistic regression to assess

[2] We do not use instrumental variables techniques, since no plausible exogenous predictor of adoption exists in the sample.

[3] This sample size is sufficient to measure treatment effects ranging between 6 and 17 % on the key outcomes of interest in our study, including: Monetary fuel expenditures, time expenditures for fuel collection, time spent cooking, preference for ethanol relative to other clean fuels, and preference for ethanol if a household's main fuel became unavailable due to a ban or other policy.

[4] Through this process, the survey team discovered that a sizeable share of customers who had purchased stoves in the target areas did not actually reside in those zones, but instead had purchased them and taken them to their location of residence. Since fuel supply was not maintained in such areas, we excluded such purchasers from the sample.

[5] By this time, COVID-19 related disruptions were no longer occurring in the study setting.

[6] We used nearest neighbor propensity score matching without replacement to draw the sample of matched controls and excluded any households from the prior survey who resided in the areas targeted by the pilot phase (and therefore would have been eligible to take up the bioethanol stove). We attempted to recontact only households in the common support region.

the relationships between the treatment variable (participation in the bioethanol program, or treatment status) and the various impact indicators (dependent variables). This approach provides estimates of the magnitude and statistical significance of intention to treat (ITT) treatment effects of the program, as it is not based on an assessment of current usage in the ethanol stove group but rather on targeting according to CCL's database. In these regressions, we control for a variety of differences between participating and non-participating, pre-matched households, and ward/district-level fixed effects.

A thematic analysis conducted by Vigolo et al. (2018) identified seven key variables influencing the selection of a cooking system, including economic factors (income), socio-demographics (e.g., gender, age, education, household composition), fuel availability, attitude towards technology, awareness of the risks of traditional cooking stoves and the benefits of improved cooking stoves (ICS), location, and social and cultural influences. The importance of many of these variables is also confirmed in Lewis and Pattanayak (2012), who found that ICS adoption and clean fuel choice were significantly associated with income, education, social status, access to credit, and location. Pye et al. (2020) studied the drivers and barriers to LPG adoption and exclusive use and found that higher education and higher income were also associated with a greater likelihood of LPG adoption.

Our regression model takes these prior findings into consideration and controls for household monthly expenditure for non-fuel items, household size, a wealth index (that includes the number of rooms in the household, use of improved water source, use of private sanitation facility, primary lighting source, number of assets), number of children under age of 18, gender of the household head, education level of household head and the primary cook, and ownership of LPG and charcoal stoves, to isolate the specific impact of the bioethanol program participation on each outcome of interest.

Ex-post PSM

The households selected for the comparison of those targeted for bioethanol fuel adoption and use were chosen based on a relatively limited set of variables. Some of those may also have changed considerably over the period between the survey from 2020 and the post-intervention survey, given the heterogeneous effects of the COVID-19 pandemic on economic well-being, and given other changes (e.g., inflationary pressures) experienced during the intervening period.

To more fully adjust for this potential selection bias, a second round of PSM was employed to enhance the comparability of the ethanol and non-ethanol adopting groups (limiting the confounding to that arising from unobservable differences). A second reason for conducting this *ex post* matching, as we discuss further below in the results, is that a number of the households drawn from CCL's database of customers ended up not identifying the ethanol stove as one of their primary cooking stoves. In the second round of PSM, we thus select more comparable ethanol and non-ethanol users by including the following variables in a first stage predicting primary use of ethanol stoves: ownership of LPG and/or charcoal stoves at the time of the follow-up survey, and a set of demographic and socio-economic characteristics (household size, number of children under 18 years of age, gender and education level of household head, education level of primary cook, literacy of household head and primary cook, a wealth index constructed from household asset ownership, and access to credit and savings indicators). The derived estimates of impacts on outcomes of interest correspond to the average treatment effect (ATE) corrected for selection on observables included in the matching equation and inclusion in the region of common support, and these may not generalize across the entire population of ethanol cooking households.

Results

Sample descriptive statistics

As noted above, the final study sample comprised 844 households. On average, there are 4 members and 4 rooms in each household. >80 % of the households have improved water facilities (in house tap, public tap, private borewell, public borewell, commercial) and have a private flush toilet or private pit latrine. Over 90 % have electricity as the source of lighting and households own 5 types of assets on average. About 67.1 % of households own an LPG stove while 85.4 % own a charcoal stove. On average, households have 1.5 children, and 16.9 % of households have a female household head. About 18.5 % of the households had taken a loan in the last year and 44.7 % had saved money. In terms of educational level, 47.2 % of household heads had a primary or lower level of education and 38.6 % had completed secondary education. 55.8 % of primary cooks in the household had a primary or lower education level and only 32.9 % had secondary education.

This sample had an overall average monthly fuel expenditure of 54,000 TZS (SD: 35,000), which is 7.3 % of the average household monthly total expenditure of 705,000 TZS. For a typical day, households spent 137 min cooking using all types of stoves on average. Monthly, households spent an average of 14.3 h (SD: 130.6) collecting fuels. Excluding fuel, a household's monthly expenditure was about 646,000 TZS. Households commonly spent around 2400 TZS on all the treatments and advice for cold & cough. For the primary cook, 15.4 % reported to have cough & cold occasionally. 0.4 % and 1.9 % suffered from burns and eye problems respectively in the past 4 weeks when the survey was conducted. On average, aggregating across all their members, households spent 5.8 h (SD: 33.3) feeling sick or caring for sick household members in the past 2 weeks.

Table 1 illustrates the similarity in means and standard deviations for key indicators following the first round of matching that was used to generate the evaluation sample. The descriptive statistics show mostly minor differences in basic household characteristics between the ethanol user sample and the non-user sample. Among the more substantial differences ($p < 0.05$), we find that treatment households tend to be more educated and are more likely to have female household heads (29 % of households in the treatment have a female household head versus only 0.8 % in the comparison group). Within the treatment group, the percentage of household heads who have a primary or less educational, secondary, and post-secondary are 38 %, 38 %, and 24 %, compared with 50 %, 39 %, and 11 % in the comparison group. Primary cooks have a lower educational level in both groups: 46 %, 40 %, and 14 % among treated households and 69 %, 24 %, and 7 % in comparison households. Other differences relate to savings and borrowing: 23 % of treated households reported taking loans in the prior year versus only 13 % for non-ethanol households, and fewer non-ethanol households reported saving money (33 % vs. 54 % in the treatment group). Finally, among treated households, 71 % owned an LPG stove and 80 % owned a charcoal stove, while about 62 % of non-ethanol households owned an LPG stove and 92 % owned a charcoal stove.

We also compare outcome variables for treated and comparison households (Table 2). The average monthly fuel expenditure of the households in the treatment group was about 58,800 TZS (SD: 36,500) at the time of the survey, but only 46,700 TZS (SD: 31,500) in the comparison group. Around 94 % of the households in the treatment group and 0 % in the comparison group reported that they had taken up ethanol as their primary stove. Among treatment households, only 6.6 % exclusively used an ethanol stove as their only primary stove, however. The reported daily usage of all stoves for cooking in the treatment and comparison groups was similar, at 177.7 min and 178.4 min. Households in the treatment group reported using the bioethanol stove for about 40.3 min of cooking per day.

This study also investigates the ethanol user households' usage and perception of ethanol. The survey results indicate that a majority of

Table 1
Sample descriptive statistics; household characteristics.

Variable Description	Overall Mean	St. Dev.	Min	Max	N	Ethanol Mean	St. Dev.	Non ethanol Mean	St. Dev.	Difference *P*-value
Household received the ethanol promotion	0.57		0	1	844	1		0		
Household size	4.3	2.2	1	14	844	4.2	2.1	4.5	2.3	0.056
Wealth index	−0.03	1.0	−3.6	1.7	827	0.026	0.96	−0.10	1.1	0.067
Number of room(s) in the household	4.3	2.4	1	22	844	3.9	2.3	4.7	2.4	0.00
Household using improved water source	0.84	0.37	0	1	844	0.83	0.38	0.85	0.36	0.43
Household using improved sanitation (no = 0, private pit latrine = 1; private flush toilet = 2)	1.3	0.71	0	2	844	1.3	0.74	1.20	0.67	0.062
Household has electric lighting	0.93	0.26	0	1	844	0.94	0.24	0.91	0.29	0.12
Number asset types household owns	4.7	1.5	1	11	842	4.9	1.5	4.5	1.4	0.0001
Number of children under age 18	1.5	1.5	0	8	844	1.5	1.4	1.6	1.5	0.58
Household head is female	0.17		0	1	844	0.29		0.008		0
Educational level of household head (primary or less = 0, secondary = 1, or post-secondary = 2)	0.76	0.75	0	2	844	0.87	0.78	0.61	0.68	0.00
Educational level of primary cook (primary or less, secondary, or post-secondary)	0.56	0.69	0	2	844	0.68	0.71	0.39	0.62	0.00
Primary cook can read a newspaper	0.96		0	1	844	0.95		0.96		0.26
Household head can read a newspaper	0.96		0	1	844	0.96		0.95		0.35
Household took any loan in the last year	0.19		0	1	844	0.23		0.13		0.0001
Household saved money in the last year	0.45		0	1	844	0.54		0.33		0.00
Household owns LPG stove	0.67		0	1	844	0.71		0.62		0.0051
Household owns charcoal stove	0.85		0	1	844	0.80		0.92		0.00

Table 2
Sample descriptive statistics; outcome variables.

Description	Overall Mean	St. Dev.	Min	Max	N	Ethanol Mean	St. Dev.	Non ethanol Mean	St. Dev.	Difference P-value
Sum of monthly fuel expenditure (TZS)	53,657.6	34,979.3	0.00	223,000.0	844	58,806.4	36,543.0	46,768.8	31,528.6	0.00
Monthly ethanol expenditure (TZS)	7292.5	13,161.3	0.00	90,000.0	884	12,743.0	15,276	0.00	0.00	0.00
Sum of monthly fuel expenditure without ethanol (TZS)	46,365.1	32,091.7	0.00	186,244.0	844	46,063.4	32,535.5	46,768.8	31,528.6	0.7500
Ethanol stove is the primary stove	0.54		0.00	1.00	844	0.94		0.00		0.00
For a typical day when ethanol stove is used, time for ONLY cooking or boiling water for tea (minutes)	12.1	22.8	0.00	180.0	844	21.1	26.8	0.00	0.00	0.00
For a typical day when all other stoves are used, time for ONLY cooking or boiling water for tea (minutes)	125.4	100.7	0.00	1830.0	844	114.3	75.0	140.3	125.9	0.0005
Total time all stoves are used for cooking or boiling water (minutes per day)	137.5	101.8	0.20	1830.0	844	135.3	79.3	140.3	125.9	0.51
Use ethanol daily or few times per week (3–4 times)	0.30		0.00	1.0	844	0.52		0.00		0.00
Use other stove daily or few times per week (3–4 times)	0.87		0.00	1.0	844	0.77		0.99		0.0016
Total household expenditure on cough & cold treatment (TZS)	2404.6	9011.9	0.00	105,000.0	844	3062.1	10,119.6	1524.9	7190.9	0.0101
Primary cook occasionally has cough & cold	0.15		0.00	1.0	844	0.17		0.13		0.14
Primary cook suffered burns (major/minor), past 4 wks	0.00		0.00	1.0	844	0.00		0.01		0.083
Primary cook suffered eye problems, past 4 wks	0.02		0.00	1.0	844	0.01		0.03		0.016
Total time household members unable to work or school because of sickness or caring for those sick with cough & cold (hours)	5.8	33.3	0.00	504.0	844	5.7	31.5	5.9	35.5	0.93
Total time household members unable to work or school because of sickness with cough & cold (hours)	4.4	27.1	0.00	432.0	844	4.2	25.4	4.7	29.2	0.76
Time spent collecting all fuels (hours)	14.3	130.6	0.00	3610.5	844	20.5	171.4	6.0	22.1	0.066
Time spent collecting ethanol (hours)	4.9	37.2	0.00	900.0	844	8.6	48.8	0.00	0.00	0.0001
Monthly expenditure other than fuel cost ('000 TZS)	640.0	1480.1	0.00	30,060.0	844	710.9	1832.8	545.2	785.4	0.076

treatment households (73.9 %), despite acquiring ethanol stoves and fuel, used ethanol less than daily over the 12 months prior to the survey. Among the 126 treatment households (26.1 %) who adopted the ethanol stove as a primary stove and reported using the fuel daily, 54 % also used at least one other fuel daily in addition to ethanol. Around 88 % of the treatment households reported that they had at least one non-ethanol fuel as a primary fuel (based on their reported primary stoves). The main reason they gave for this was that ethanol was too expensive (44 %). In addition to the cost, other reasons for not using ethanol daily included difficulties in refilling canisters (26 %), preference for the convenience of cooking with other fuels (12 %), lack of confidence about use of ethanol (10 %), preference for the taste of cooking with other fuels (6 %), and a perception that the ethanol stoves were too expensive (2 %).

For those households that reported the ethanol stove as a primary stove, 72 % indicated that they believed ethanol was affordable, 20 % considered it easy to refill canisters, 15 % preferred the convenience of cooking with ethanol, 9 % found ethanol stoves to be affordable, and 3 % favored the taste of food items cooked with ethanol. However, they also encountered challenges with ethanol use, including the rapid consumption of ethanol fuel and evaporation of fuel from the stove (29 %), the cost of ethanol (22 %), and problems in refilling canisters (13 %).

Intention to treat results comparing households with and without ethanol stoves

Fuel expenditures

The first main result from the simple OLS regression comparison of households acquiring ethanol stoves (the treatment group) and comparison households, controlling for other covariates, is that the adopting customers have higher monthly overall fuel expenditure, monthly ethanol expenditure, and report increased time spent obtaining all fuels including ethanol. Interestingly, they do not appear to spend significantly less money on non-ethanol fuels, which suggests that little if any alternative fuel is displaced when households add ethanol to their mix of energy sources. Participants in this program had significantly higher total monthly fuel expenditure, by about 12,300 TZS, and 13,800 TZS higher monthly ethanol expenditure (Table 3). In log-level specifications that reduce the skewness of the distribution of monthly expenses, we find that ethanol stove adoption is similarly associated with substantially higher total and ethanol monthly fuel expenditure.

Other factors are statistically significant determinants of household fuel expenditures. In the regression analysis, we observe that the number of household members (household size), ownership of an LPG stove, ownership of a charcoal stove, the educational level of household head, and having money saved are all significantly related to higher monthly fuel expenditure. Households that own a charcoal stove have, on average, about 24,600 TZS higher monthly fuel expenditure compared to households that do not. Households that own an LPG stove spend 10,600 TZS more on monthly fuel than households that do not own an LPG stove. On the other hand, owning an LPG stove is related to about 3400 TZS lower monthly ethanol expenditure. Households with heads that finished secondary education spent more on all fuels but less on ethanol, while households with primary cooks who finished secondary education had higher ethanol expenditures. Having savings is negatively related to expenditure on all fuels, but positively related to expenditure on ethanol. Households with female heads have lower ethanol expenditures. Finally, we observe positive associations between larger household size, owning an LPG stove, and owning a charcoal stove, and monthly expenditure on fuels other than ethanol.

Time spent obtaining cooking fuels and time spent cooking

On average, households acquiring ethanol stoves also spent 74.3 % more time obtaining fuels per month compared to those in the non-ethanol group, after controlling for the effects of other variables. Treatment households spent 7.2 h (94.0 % more hours) per month obtaining ethanol, but this additional collection is heavily right-skewed, implying that ethanol procurement is highly inconvenient for a minority of households. In addition, this increase could be attributed to the infancy of the program and the fact that there were still relatively few fuel outlet centers in the program areas at the time of the survey, a situation that could change in the future.

Households with access to loans, and with a primary cook having post-secondary education, spent more time obtaining fuel (Table 4). Wealth, having a female household head, primary cook's completion of secondary education, and owning an LPG stove were all associated with lower time spent obtaining fuel. Households owning a charcoal stove, having a female household head, or owning an LPG stove spent less time collecting ethanol, while households with savings and access to credit spent more time.

The regression results reveal that ethanol stoves were used about 20.9 min per day, and counterintuitively, that bioethanol users spent 15 min more on any cooking than comparison households using all types of stoves. The amount of time ethanol stoves are used is again influenced by other variables. Households with savings used their ethanol stove on average 6.2 min/day more than those without. Households owning LPG and charcoal stoves used the ethanol stoves 10.2 min less, and 6.9 min

Table 3
OLS regression comparing fuel expenditures for households targeted by the bioethanol promotion and comparison households.

Variable	1. Total fuel expenditure (TZS)		2. Ethanol fuel expenditure (TZS)		3. Other fuel expenditure (TZS)		4. Log (Total fuel expenditure)		5. Log (Ethanol expenditure)		6. Log (Other fuel expenditure)	
	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.
Treatment	12,326.5***	−3146.2	13,823.5***	−1079.6	−1497.0	−2824.9	1.2***	−0.23	8.1***	−0.24	0.24	−0.27
Monthly expenditure, w/o fuel	0.001	0	0	0	0	0	0	0	0	0	0	0
Household size	4015.7***	−885.5	146.4	−302.3	3869.3***	−815.3	0.013	−0.06	−0.13	−0.07	0.051	−0.06
Wealth index	2144.8	−1431.8	471.7	−477.0	1673.1	−1304.9	0.12	−0.09	0.16	−0.12	0.051	−0.11
# members < 18 yrs old	−469.0	−1250.0	55.0	−480.2	−524.0	−1120.1	0.062	−0.08	0.12	−0.11	0.12	−0.09
Female household head	−4011.1	−3093.2	−1255.0	−1553.8	−2756.1	−2733.2	−0.01	−0.14	−0.87*	−0.36	0.42	−0.24
HH head: secondary education	271.6	−2995.9	−2041.9	−1106.7	2313.5	−2655.2	0.36*	−0.17	−0.58*	−0.25	0.36	−0.23
HH head: post-secondary	3479.1	−4394.8	−2204.8	−1754.6	5683.9	−3830.8	0.14	−0.26	−0.41	−0.33	0.053	−0.30
Primary cook: secondary	5113.9	−2722.1	287.0	−992.0	4826.8	−2519.8	0.059	−0.15	0.58*	−0.25	−0.044	−0.20
Primary cook: post-secondary	4059.7	−5048.4	1700.7	−2196.4	2359.1	−4510.1	0.098	−0.24	0.16	−0.41	0.30	−0.30
Primary cook: Can read	−5189.5	−8000.6	−1429.9	−3459.1	−3759.6	−6321.8	0.49	−0.55	0.095	−0.48	−0.17	−0.56
HH head: Can read	8095.9	−6768.7	2948.0	−2668.4	5147.9	−5601.7	−0.61	−0.54	0.17	−0.39	−0.54	−0.53
Loan in past year	1526.4	−3128.0	1511.2	−1261.3	15.2	−2836.5	−0.21	−0.19	0.29	−0.28	−0.23	−0.23
Savings in past year	−2508.6	−2254.0	2424.4*	−940.6	−4932.9*	−2044.4	−0.44**	−0.15	0.47*	−0.22	−0.48**	−0.18
Own LPG stove	10,619.6***	−2403.3	−3428.3***	−1009.6	14,047.8***	−2130.2	0.31*	−0.15	−1.1***	−0.22	1.6***	−0.22
Own charcoal stove	24,562.7***	−3309.1	−799.6	−1670.5	25,362.3***	−2821.9	0.65*	−0.26	0.21	−0.32	3.2***	−0.43
Missing expenditure	−6841.1	−4277.9	−1177.4	−1324.0	−5663.8	−4032.2	−0.061	−0.21	−0.73	−0.41	0.11	−0.28
HH head: education missing	7220.4*	−3578.3	594.7	−1147.2	6625.7*	−3221.0	0.15	−0.15	0.26	−0.32	0.18	−0.22
Primary cook: education miss	7553.7*	−3731.7	−280.2	−1097.2	7833.9*	−3377.4	0.18	−0.13	0.28	−0.29	0.074	−0.24
Constant	3579.5	−8444.6	396.3	−2740.0	3183.2	−7730.1	9.7***	−0.43	0.819	−0.67	7.0***	−0.63
R2	0.37	0.37	0.33	0.33	0.39	0.39	0.54	0.54	0.73	0.73	0.52	0.52
N	827	827	827	827	827	827	827	827	827	827	827	827

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.00$; Ward fixed effects are controlled for all six models; For categorical variables education level of household head and education level of primary cook, the reference category is having primary or less education level. The unit of expenditure is TZS.

Table 4
Regression comparing other outcomes for households targeted by the bioethanol promotion and comparison households.

Variable	1. Time spent obtaining fuel		2. Ethanol stove cooking time		3. All stove cooking time		4. Primary ethanol use		5. Frequent ethanol use		6. Primary cook has cough/cold		7. Time sick/caring for sick		8. Expenditure on cough and cold	
	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.	Coef.	St.err.
Treatment	23.0	−14.3	20.9***	−1.6	15.0*	−6.8					0.87**	−0.32	−0.35	−4.6	2253.1*	−1101.6
Monthly expenditure, w/o fuel	0.0	0.0	0.0	0.0	0.0	0.0			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Household size	0.68	−1.1	−1.0	−0.56	7.1***	−1.9	−0.07	−0.07	−0.14*	−0.07	0.009	−0.09	0.44	−1.08	176.8	−220.1
Wealth index	1.8	−5.2	1.0	−0.83	3.4	−3.3	−0.03	−0.11	0.05	−0.11	0.089	−0.16	1.5	−2.09	297.1	−427.6
# members <18 yrs old	−1.7	−2.4	−0.20	−0.72	0.0	−2.8	0.10	−0.09	0.14	−0.10	0.022	−0.14	0.86	−1.3	488.1	−297.8
Female household head	−11.2	−10.7	−3.6	−2.5	−12.4	−6.9	1.9***	−0.25	0.85***	−0.22	−0.092	−0.42	−2.5	−3.6	−724.3	−953.8
HH head: secondary education	5.4	−7.1	−2.3	−1.8	5.1	−6.8	0.06	−0.23	0.14	−0.25	−0.31	−0.37	−4.9	−3.2	101.9	−795.1
HH head: post-secondary	−18.4	−17.7	−4.4*	−2.1	17.4*	−7.7	0.67*	−0.28	0.46	−0.30	0.28	−0.39	−1.6	−4.6	1713.7	−1343.3
Primary cook: secondary	−13.2	−10.6	0.6	−1.7	−7.3	−6.4	1.1***	−0.20	0.11	−0.22	−0.67	−0.35	−4.0	−2.2	−755.8	−873.4
Primary cook: post-secondary	41.4	−42.3	−2.2	−2.2	−11.7	−9.1	0.44	−0.33	0.10	−0.34	−0.11	−0.51	−3.5	−3.7	−1936.0	−1352.3
Primary cook: Can read	3.0	−17.7	−2.0	−4.3	4.9	−18.5	−1.9**	−0.62	−0.71	−0.56	0.047	−0.69	12.8*	−5.4	2490.0	−1850.3
HH head: Can read	−14.2	−16.2	−5.2	−3.9	6.8	−19.8	1.02	−0.56	0.70	−0.53	0.49	−0.99	−0.16	−3.5	−136.5	−1357.0
Loan in past year	26.6	−23.6	−2.7	−1.9	−2.9	−6.5	0.35	−0.22	0.21	−0.22	0.14	−0.30	6.9	−4.7	−150.6	−1085.7
Savings in past year	1.4	−5.6	6.2***	−1.6	−3.4	−6.5	1.1***	−0.18	1.0***	−0.19	0.80**	−0.28	−4.3	−3.1	242.0	−771.1
Own LPG stove	−2.2	−5.2	−10.2***	−2.4	23.6***	−6.5	−0.06	−0.20	−0.94***	−0.21	−0.56	−0.31	−2.6	−2.7	511.7	−711.5
Own charcoal stove	11.4	−19.9	−6.9**	−2.7	58.6***	−7.8	−0.44	−0.28	−0.40	−0.25	3.0***	−0.60	3.6	−2.1	298.1	−1008.4
Missing expenditure	28.2	−15.5	−0.6	−2.0	−37.3***	−9.2	−2.1***	−0.50	−2.4***	−0.67	−0.018	−0.72	0.29	−3.4	−147.0	−532.8
HH head: education missing	48.3	−45.9	1.0	−2.9	28.5**	−9.4	−0.77**	−0.28	−1.1**	−0.36	−1.0	−0.87	−0.035	−1.9	−553.4	−528.0
Primary cook: education miss	−25.6	−20.5	−3.3	−1.8	7.3	−7.8	0.19	−0.27	−0.79*	−0.36	−1.3	−0.89	−3.9*	−1.7	−1327.7*	−580.5
Ward fixed effects	Yes		Yes		Yes								Yes		Yes	
District fixed effects							Yes		Yes		Yes					
Constant	−3.2	−17.3	13.5*	−6.2	28.0	−19.2	0.4	−0.5	−0.2	−0.5	−6.1***	−1.1	−15.3	−8.5	−4242.7*	−1806.4
R2	0.12	0.12	0.41	0.41	0.36	0.36	0.21	0.21	0.16	0.16	0.40	0.40	0.11	0.11	0.17	0.17
N	827	827	827	827	827	827	827	827	827	827	827	827	827	827	827	827

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; For categorical variables education level of household head and education level of primary cook, the reference category is having primary or less education level.

less, respectively. Adding one household member decreased the time spent cooking with ethanol by about 1 min/day (this correlation is not statistically significant). Meanwhile, female headed households used ethanol stoves 28.9 % (8.03 min in mean) less than those having a male head. There were also significant correlations between the ethanol program participation and daily usage of all stoves. An additional household member increased the time using all stoves by 7.1 min/day. Owning LPG and charcoal stoves was associated with more total stove use, by 23.5 min and 58.6 min, respectively. These general patterns of increased cooking time suggest stacking that increases cooking energy use (Ruiz-Mercado & Masera, 2015); they are also consistent with the patterns for cooking fuel expenditures – increased spending on ethanol that is not offset by similar reductions in other purchased fuels.

We further find that households with a female household head have significantly higher likelihood of having an ethanol stove as their primary stove. Household heads having post-secondary education, primary cooks having secondary education, and having savings are also related to higher likelihood of primary ethanol stove use.

Frequent usage of ethanol stove is defined as the household using ethanol stove at least a few times per week (the next more frequent use category is daily use, and the next less frequent is once per week). An increase in household size by one member is associated with a decrease of 13.1 % in the odds of frequent usage of ethanol stove. Similarly, female headed households and households with savings are more likely to engage in frequent usage. Households owning an LPG stove have 60.7 % lower odds of frequent usage of the ethanol stove.

Reported health conditions

Focusing specifically on respiratory health, we investigated the factors associated with several outcomes: a primary cook's cough and cold symptoms, the total amount of time members were unable to work or go to school because they were sick with cold & cough, and the total amount of time members were too sick or taking care of other sick members. Our intention-to-treat regression results produce counterintuitive findings (Table 4): Primary cooks in the ethanol user households are 87 % more likely to report having cold & cough than non-user households over the two weeks prior to the survey. Primary cooks also have a higher likelihood of having cough and cold if their household has money saved and owns a charcoal stove. The regressions for health conditions also demonstrate a statistically significant relationship between being in the ethanol program and households' total expenditure on cough and cold treatment over the month prior to the survey. On average, ethanol user households spent about 2250 TZS more per month than non-user households.

We also assessed the associations of these same factors with primary cooks' burns and eye problems. The only statistically significant finding is that households with an LPG stove had 79.1 % lower odds of reporting that their primary cook had eye problems over the prior 4 weeks.

PSM results: Average treatment effects

As the analysis above makes clear, a number of households in the ethanol stove group did not actually identify that stove as a primary stove when we conducted our survey, though they had been targeted by the program and had initially taken it up. As such, they are ITT estimates that may not indicate the true effect of using ethanol fuel. A second concern is that some of the results presented above may be subject to selection bias, given pre-existing differences between households in the treatment and comparison groups. In this study, we thus estimate the Average Treatment Effect (ATE) using PSM, to better isolate the causal impact of primary use of ethanol in the sample population.[7] Compared to "observationally" similar non-user households, primary users of ethanol had statistically higher household monthly fuel expenditure (ATE = 13,484 TZS) and monthly ethanol expenditure (ATE = 13,342 TZS) (Table 5). Similarly, the treatment group spent more time daily cooking with an ethanol stove (ATE = 23 min per day). Moreover, among these treated households, the time spent collecting ethanol was 7.3 h per month higher than that of untreated households, while time spent collecting all fuels was also higher (ATE = 18.3 h per month).

Other differences were small and not statistically significant. For example, we found that primary ethanol users had essentially the same total fuel expenditure on fuels other than ethanol (ATE = 142 TZS), spent roughly the same amount of time daily cooking with all stoves (ATE = 1.9 min per day), and had similar household expenditure on illness (ATE = 1615 TZS per month), frequency of cough and cold of primary cook in the two weeks prior to the survey (ATE = −2.3 %), time spent unable to work due to cough and cold in the two weeks prior to the survey (ATE = +0.2 h), time spent unable to work and caring for other sick household members in the two weeks prior to the survey (ATE = +1.3 h), and daily time spent using non-ethanol stoves (ATE = −0.4 min per day). All of these results are consistent across other matching specifications – namely using kernel or radius matching algorithms (see Supplementary materials). Thus, some of the apparent differences found in the ITT analysis do appear to stem from differences across households that are unrelated to primary use of the ethanol stove.

Table 5
Average treatment effect (Comparison of key outcomes for treatment and comparison households: Nearest neighbor matching).

Description	ATE	SE
Monthly fuel expenditure (TZS)	13,484.2**	4232.9
Monthly ethanol expenditure (TZS)	13,342.4***	755.7
Monthly fuel expenditure, w/o ethanol (TZS)	141.8	4142.8
Time using stoves per day (minutes)	1.86	11.6
Expenditure on cough and cold treatment in the past month (TZS)	1614.5	1091.4
Primary cook occasionally having cough & cold	−0.023	0.046
Time being unable to work or go to school because he/she had cough and cold or was caring for other sick members in the past 2 weeks (hours)	0.19	10.8
Time being unable to work or go to school because he/she had cough and cold in the past 2 weeks (hours)	1.31	3.64
Having ethanol stove as the primary stove	1.0***	0.0
Time using ethanol stoves per day (minutes)	22.7***	1.4
Time using non ethanol stoves per day (minutes)	−0.44	0.87
Time collecting all fuels per month (hours)	18.3*	9.3
Time collecting ethanol per month (hours)	7.3**	1.48

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

[7] Our reported results correspond to nearest neighbor matching that limits the comparison to households in the common support region and trims the 10 worst matches. The first stage logit results (Table S1) and balancing properties (Figure S1) for the resulting matched sample are summarized in the supplementary materials, along with alternative radius (with caliper of 0.1 and similar trimming) and kernel (with bandwidth set to 0.05) matching specifications, and their balancing plots (Figures S2 and S3). The matched sample is well balanced on observables, relative to the pre-matched sample.

Discussion and broader implications

Expected findings

This paper makes several contributions to understanding the economic and health benefits of programs that provide affordable access to bioethanol stoves and fuel. Based on the multiple regression and propensity score matching results of ethanol users and non-users, ethanol stove adoption was found to increase cooking time with that fuel and self-reported primary use of ethanol cooking, both of which are good signals that the fuel and stoves were accepted and were being used by many targeted households. We also expected that stacking of multiple cooking technologies would result, consistent with prior literature on clean cooking fuel transitions in low-income country contexts.

Unexpected findings

Ethanol user households were expected to benefit in several dimensions (reduced fuel expenditure, at least for alternative fuels, cooking and fuel collecting time savings, and health improvements). However, we found very little evidence of monthly fuel expenditure savings attributable to the ethanol promotion program, as ethanol users were found to spend more on both ethanol (as expected) and total fuel expenditure (this was not expected, as we thought the ethanol spending would offset spending on other fuels, given the program goal of competitive pricing of ethanol). Moreover, time spent collecting both ethanol (again expected) and all fuels (not expected) was higher among the primary users of ethanol stoves. Finally, the average cooking time reported using all stoves daily was also higher in the ethanol-using group (though not in the ATE results). These effects on time use and expenses likely reflect the fact that most primary users of ethanol continued to use other fuels and may also indicate that ethanol stoves were not convenient to use for some cooking purposes. Another possibility is that introducing a new ethanol stove in the household increased the amount of cooking done by households. It is also worth noting that higher reported cooking time may stem from concurrent use of multiple technologies, since time use measures were elicited on a stove-wise basis (rather than using time budgets or diaries).

Finally, ethanol adoption was not clearly linked to health improvements as reporting of cough and cold by the primary cook, and the time spent sick or caring for sick household members did not decrease in a statistically meaningful way. This lack of discernible health benefits is not inconsistent with other literature (see, e.g., Mortimer & Balmes, 2018; or Checkley et al., 2024), especially when considering the persistence of stacking with charcoal, itself a highly polluting household fuel (Shankar et al., 2020). Other factors that may have reduced our ability to detect health improvements may include the insufficient time following the intervention to observe health improvements, measurement error in self-reported variables, or confounding factors such as ambient air pollution exposure. Another possible confounding issue was the slightly different timing of the surveys among ethanol users and non-users (due to the logistics of using a matching design to ensure comparability of the ethanol users with selected controls). The surveys with users took place in May–July whereas those with non-ethanol using comparison households were conducted in August and September.

Broader implications

While the program was successful in increasing ethanol stove usage, the generally mixed findings from this evaluation highlight the need for program improvements. A key concern is the lack of evidence that adoption of ethanol cooking helps households reduce fuel expenditures and time spent cooking. A large share – 40 % of the treated households – said that they perceived ethanol to be expensive, regardless of whether they used that fuel as their primary cooking energy source. Therefore, policy measures such as subsidies and value-added tax (VAT) reductions to further lower the price of ethanol fuel appear necessary to increase the affordability of ethanol cooking, and to make that fuel more competitive with others available in the market. This will become ever more important during larger scale-up given the fuel's limited local production and high import costs (Benka-Coker et al., 2025). Moreover, as the program begins to target peri-urban and rural areas, it seems likely, based on prior evidence and on the challenges to cooking energy transitions away from urban centers, that demand will be lower, even as supply costs rise (Das et al., 2024).

It may also be necessary to intervene more strongly to discourage use of traditional stoves and fuels, especially charcoal, via information and social marketing campaigns that promote healthier cooking habits, or interventions that decrease the price competitiveness of that fuel (Doggart et al., 2020). However, policy interventions such as taxes and quotas to control charcoal usage may face significant challenges and political headwinds due to the strong reliance of Dar es Salaam residents on charcoal for cooking (Benka-Coker et al., 2025; MNRT, 2022). The prevalence of stacking may also be due to other advantages of alternative fuels and stoves that could be reduced with concerted policy intervention focusing on enhancing ethanol availability, such as (1) improving ethanol fuel accessibility in the marketplace by forming a better network of small retail shops or increasing the direct marketing subsidy paid to the retailers (CCL); and (2) allowing more convenient purchases of smaller quantities, which has been successfully implemented by CCL by putting out a 0.75 l bottle of fuel.

The design of the ethanol stoves should also be improved as about 20 % of the ethanol user households reported that it was difficult to refill the canisters and 5 % had experienced ethanol leakage from the stove and what they believed to be overly rapid consumption. Ethanol stove improvements that would make it more versatile for meeting households' diverse cooking needs and address concerns about ethanol fuel evaporation (e.g., developing and distributing an inexpensive snap-on silicone lid that seals the fuel canister when it is not in use) appear essential. Households reported substantial dissatisfaction with the convenience and appropriateness of cooking with ethanol, which may have reduced their willingness to more fully switch away from traditional fuels.

CCL faced several obstacles, including difficulty in persuading local shops to stock ethanol fuel and establish a robust market structure, distrust from local communities, limited consumer demand, and low profit margins (Benka-Coker et al., 2025). It encountered challenges in aligning its sales model and pricing strategies with the local context, due to the disconnect between the initial project design and realities on the ground. Establishing a consistent and reliable retail presence for ethanol fuel proved to be particularly challenging for the program as most fuel suppliers in Dar es Salaam are last-mile shops with limited capital that frequently close or relocate. And though this program had been piloted in Zanzibar, the initial project design did not fully translate to the realities of Dar es Salaam; adjustments were therefore needed to increase sales, contributing to perceptions of program ineffectiveness and inefficiency, and reducing consumer trust in ethanol cooking (Benka-Coker et al., 2025). An important lesson is that implementation details matter when scaling up new cooking technology. For ethanol cooking in particular, in line with prior work, resolving several recurrent problems seems crucial:

(1) Securing a high quality, reliable, and financially sustainable supply of ethanol, which is dependent on producers' willingness to make this product available as a cooking fuel (Mudombi et al., 2018; Osiolo et al., 2024);
(2) Offering better follow-up maintenance for equipment (Mudombi et al., 2018);
(3) Forming stronger partnerships with last-mile shops for advertising, marketing, and education to improve confidence in ethanol supplies and build local trust (Benka-Coker et al., 2025; Ozier et al., 2018; Pattanayak et al., 2019);

(4) Enhancing affordability of ethanol, relative to other fuels (Charron et al., 2011; Mudombi et al., 2018; Ozier et al., 2018); and.
(5) Fully localizing the program to better align with contextual constraints (Jeuland et al., 2018; Benka-Coker et al., 2025).

Conclusion and limitations

An ethanol promotion program in Dar es Salaam, Tanzania achieved success in raising visibility for ethanol as a cooking alternative, drawing interest and attention of government officials and policymakers, fostering a more supportive political environment, and attracting new financial support for clean cooking initiatives in Tanzania (Benka-Coker et al., 2025). Unfortunately, a number of flaws ultimately limited the success and impacts of the initial phase of project implementation. These challenges bring to the fore several important lessons that can help to improve this program, and inform the design of future cooking energy transition programs. First, it is essential to tailor such programs to fit local settings, such as market structures and cooking habits, and involve local people and knowledge in the program design stage. Second, different advertising and education approaches, such as radio, television, and newspaper if allowed, should be adopted to increase awareness and build trust. Third, robust supporting policy interventions are necessary.

Our study is one of the very first impact evaluations assessing a scaled-up ethanol promotion intervention under real-world conditions, and one of the only evaluations of clean cooking interventions more generally in a major African city. Nonetheless, it has several limitations that future research should address. First, our study focused on low and middle-class households in Dar es Salaam, Tanzania. Future studies might consider enrolling a larger sample within this city or, if the program is replicated outside of the capital, across the country. Second, emissions reductions were not evaluated, due to budget limitations. Collecting data on domestic air pollution could help to better understand the environmental and health impacts of ethanol stove adoption. Third, due to constraints on the study design, interviews with matched control households could only be conducted after those with treatment households, introducing the possibility that seasonal differences might have influenced the results, though all surveys were completed during the dry season. Fourth, due to the limited data availability, some contextual variables that may influence health outcomes could not be included in the analysis, such as kitchen ventilation, having a separate kitchen, unobserved cultural practices, and smoking behavior of household members (Capuno et al., 2018). However, the effects of such variables are partly accounted for given their high correlation with income, education, and other included variables (Capuno et al., 2018). Fifth, the experiences and pattern of this ethanol promotion project, and for the particular matched sample that we consider, may not generalize across the whole of Dar es Salaam or to other regions. Finally, this study only examined the beneficiary side, while complementary work also applied an implementation science approach to understanding program aspects, future work should further delve into Tanzania's regulatory environment to better assess how program improvements could be made.

To conclude, impact evaluations such as this one, and studies that examine implementation details and relate those to the context of interventions, are needed for clean fuel and cookstove programs to further study the social, economic, health, and environmental consequences of project designs and to help learn from implementation challenges. The transition from traditional and polluting fuels to clean energy is driven by complex social and economic factors that remain poorly understood (Mudombi et al., 2018). Persistent fuel preferences and usage patterns highlight the need for further studies, building on this one, of what policy and program interventions can effectively improve clean energy access and shift users' behavior and perceptions towards safer, healthier, and more sustainable cooking stoves and fuels.

CRediT authorship contribution statement

Wenrui Qu: Writing – original draft, Formal analysis, Data curation. **Remidius Ruhinduka:** Supervision, Project administration, Methodology, Investigation, Conceptualization. **Maggie L. Clark:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization. **Megan Benka-Coker:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Ashlinn Quinn:** Methodology, Funding acquisition, Conceptualization. **Harry Stokes:** Writing – review & editing, Investigation. **Wubshet Tadele:** Writing – review & editing, Investigation. **Marc Jeuland:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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