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An Analysis of Sustainability in Water and Energy Product Implementation

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AN ANALYSIS OF SUSTAINABILITY IN WATER AND ENERGY PRODUCT IMPLEMENTATION IN RURAL RWANDA

by

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Abstract

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An Analysis of Sustainability in Water and Energy Product Implementation in Rural Rwanda

Thesis directed by Professor Karl G. Linden

Public health interventions which aim to address contaminated drinking water and indoor air pollution in developing countries may help to reduce the burden from two of the leading causes of death, diarrhea and pneumonia. Interventions which distribute and promote household water filters may reduce diarrheal disease through improving water quality, while improved cookstove interventions may reduce indoor air pollution, a leading cause of pneumonia. Beyond health impact, water filter and cookstove interventions may provide livelihood and environmental impacts which can contribute to the overall suitability and sustainability of an intervention. Household water filtration has the potential to both reduce fuelwood consumption and provide time savings by no longer needing to boil water before drinking. Similarly, improved cookstoves have the potential to reduce fuelwood purchasing and collecting, while providing environmental benefits both locally and globally.

This research describes a public health intervention where water filters and improved cookstoves were distributed in rural Rwanda. The intervention is examined from the pilot phase to a scale up of over 100,000 households, examining adoption rates and behaviors while performing a cost benefit analysis to determine if the program provided sufficient benefits to outweigh program costs. High uptake and sustained adoption was measured from the pilot phase through the large-scale program with over 90% measured adoption rates. However, exclusive use of both technologies was identified as a concern in providing health impact. The program was estimated to be highly beneficial with benefits providing over six times the cost of the program. Fuel savings from the cookstove were found to be the most dominant contributor to the positive benefit to cost ratio.

An additional sub-study was conducted to analyze environmental, economic and social sustainability metrics of locally made and imported cookstoves. Both were found to contribute significantly but by different means. The imported stove tended to provide higher benefits from an environmental perspective while the locally made stove provided many social benefits. Economic sustainability was mixed based on wood procurement scenarios. Overall a hybrid approach is likely to provide the most sustainable benefits.

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Table of Contents

Introduction

Nearly 7 million deaths each year are a result of diarrheal disease and pneumonia, with over 2 million deaths of children under five[1]. Much of this disease burden can be attributed to a lack of access to improved drinking water and clean energy sources for cooking. Globally, 750 million people don't have access to safe water[2] while nearly three billion rely on open fires to cook their food[3].

Public health interventions which aim to reduce exposure to contaminated water and indoor air pollution may help to combat diarrhea[4] and pneumonia[5,6]. Such interventions may include the implementation or advocacy for water treatment technologies such as boiling, chlorination, filtration and solar disinfection, in the treatment of unsafe drinking water[7,8]. While interventions involving use of improved cookstoves may reduce harmful airborne pollutants from dirty cooking methods[9,10].

Just as significant as health benefits, are the livelihood and environmental benefits from public health programs. Advocacy of household water treatment methods replacing boiling can both reduce fuelwood consumption and provide time savings[11,12]. Similarly, implementation of improved cooking stoves has the potential to reduce expenditures on purchasing fuelwood, and time from both collecting fuelwood and cooking. Additionally reduction in fuelwood consumption can result in significant environmental benefits both locally through reduced deforestation and globally through reduced greenhouse gas emissions[13–16].

In Rwanda, implementation of safe drinking water programs may help to reduce the 8% of deaths of children under five from diarrhea[17], while improved cookstoves could contribute to a reduction in the over 12,000 deaths from indoor air pollution[3]. Such programs could also provide significant contributions to livelihood and environmental benefits. In a country of nearly 10.5 million people, of who over 82% depend on firewood as their main source of energy for cooking and 42% boil their water prior to drinking[18], decreased wood demand from water treatment methods and improved cookstoves could help reduce the deficit in sustainable availability of firewood[19]. Additionally with approximately 80% of Rwandans living on less than $2 per day[20], cost savings from reduced fuelwood purchasing has the potential to benefit individual households daily expenditures.

However, public health programs advocating water treatment methods and improved cookstoves can vary greatly in quality, scale and impact, from small community driven projects to large scale government programs, from non-profit to for-profit models, and from subsidized to market based funding mechanisms. Because of the high degree of variability of impacts between all of these program models, understanding a particular program's ability to deliver benefits to the target population in a cost effective and sustainable way is essential to inform future interventions.

This study aims to study one such large-scale intervention in rural Rwanda, examining the drivers to sustainable program design and its ability to provide benefits to the target population. The *Tubeho Neza* ("Live Well") program, is a partnership between the Rwanda Ministry of Health (MOH) and the social enterprise, DelAgua Health (DelAgua), to deliver environmental health technologies to the poorest 25% of Rwanda's population. The program includes the distribution of the EcoZoom Dura improved wood burning cookstove and the Vestergaard Frandsen LifeStraw Family 2.0 household gravity-fed water filter. The intervention includes household level education and behavior change messaging to each household through MOH Community Health Workers. Long term, the program offers maintenance and repair as well as on-going education activities to promote sustained usage of the products. The program is privately financed and earns revenue from carbon credits under the United Nations Clean Development Mechanism.

The program began in the fall of 2012, where a pilot phase of approximately 2000 households in 15 villages was conducted. Following the results of several studies on the pilot, the program was scaled to over 100,000 households in the Western Province of Rwanda in 2014, using lessons learned. All households categorized as *Ubudehe* 1 or 2, the government recognized poorest 25% of households, received the products and educational messaging.

The primary objective of this research is to evaluate the overall sustainability of the *Tubeho Neza* public health program in Rwanda, analyzing the program from the pilot phase through the scale up of 100,000 households. Sustainability was examined from the following perspectives:

- Adoption – Is the program accepted by the target population and why? The first fundamental facet of a sustainable program is actual use of technologies. Without meaningful adoption rates and positive behaviour change, a program will not last beyond the short term and thus long-term sustainability will not be realized.
- Cost Benefit – Does the program provide enough benefits to outweigh its cost? While a program may aim to provide a specific benefit to the target population, it can only be sustainable if the inputs into the program result in substantial impact. Scarce resources spent on programs with little benefit will not provide overall sustainability to the international development sector.

- Technology Selection – Do locally made products or imported products provide greater benefits from an environmental, social and economic perspective? Products should be measured based on a holistic approach whereby all metrics of sustainability are considered. Imported and locally made products have value in differing sustainability metrics and must be considered as a whole during product selection.

The three hypotheses outlined below will be used to evaluate the objectives:

- The free distribution of water filters and improved cookstoves combined with an extensive behavior change program, financed in a "pay for performance" public-private partnership, will result in adoption of the technologies within the majority of a 2000 household pilot during the initial five months following distribution of the products.
- Benefits of the intervention program at scale will outweigh program costs.

  a) A large scale-up (50 fold) increase to the pilot program will result in comparable adoption magnitude among the target population.

  b) At scale, monetized program benefits beyond direct health impacts (fuel savings, time savings and environmental benefits) will be greater than the cost of the intervention program.
- A hybrid improved cookstove, designed based on principles of an imported stove, manufactured locally, utilizing the supply chain of a locally produced stove and sourcing raw materials both regionally and locally will provide a more optimized design in respect to a holistic sustainability approach.

  a) The locally produced stove has a lower lifecycle cost compared to the imported stove.

  b) The imported stove is more economically sustainable compared to the locally produced stove.

  c) The imported stove is more socially sustainable with regards to reproducibility and scalability while the locally produced stove is more socially sustainable on local job creation.

d) Neither stove provides a significant benefit to social sustainability from a health impact perspective.

Four studies were conducted to assess the hypotheses:

- **Study One:** *Designing and Piloting a Program to Provide Water Filters and Improved Cookstoves in Rwanda* – The primary program criteria which includes an integration of a behaviour change messaging campaign, free distribution of environmental health technologies and a public private partnership, are taken as a whole to evaluate if meaningful uptake of the water filters and improved cookstoves is demonstrated over an initial adoption period of five months.
- **Study Two:** *Process Evaluation and Assessment of Use of a Large Scale Water Filter and Cookstove Program in Rwanda* – An assessment of the 50 fold scale-up of the pilot program to determine if comparable adoption rate are measured relative to the pilot program.
- **Study Three:** *A Cost-Benefit Analysis of Livelihood and Environmental Impacts Within a Large Scale Water Filter and Improved Cookstove Distribution in Rwanda* – Determine if monetized livelihood and environmental program benefits outweigh the overall cost of the program through a cost benefit analysis.
- **Study Four**: *Assessing Improved Cookstove Sustainability: An Evaluation of Locally Manufactured and Imported High Efficiency Rocket Stoves in Rwanda* – Sustainability metrics are analysed to characterize the sustainability of imported and locally made cookstoves.

Literature Review

A brief summary of relevant background information is summarized in this section. However, each of the four studies in the following chapters outlines the current literature in more detail.

Study One: *Designing and Piloting a Program to Provide Water Filters and Improved Cookstoves in Rwanda*

Study Two: *Process Evaluation and Assessment of Use of a Large Scale Water Filter and Cookstove Program in Rwanda*

While no known literature exists on programs which include a dual water and energy intervention, several studies assess drinking water quality programs and improved cookstove programs independently.

Earlier versions of the intervention filter were shown to have 96% adoption in Zambia[12] after 12 months and 68% adoption in the Democratic Republic of Congo after eight months[21]. Additionally, compared to other point-of-use water methods, filtration often has higher adoption rates[22] possibly because it is seen as easier to use[23] and doesn't result in a change in taste and odor[24]. A key observation with many drinking water interventions is occasional consumption of untreated water outside of the home. Even occasional consumption of untreated water can greatly reduce the potential health benefits from water quality interventions[25,26] and thus this particular aspect needs to be characterized within the *Tubeho Neza* program.

Literature evaluating improved cookstoves explains a theory called "stove stacking" where the household uses multiple stoves for varying purposes. Studies have shown that households do not move from older existing methods of cooking such as a 3-stone fire to exclusive use of an improved stove possibly due to the improved stove not meeting the user's traditional cooking needs[27–29]. Therefore a careful examination of cooking practices in the *Tubeho Neza* program will be necessary in evaluating any adoption rates.

Much of the focus of these studies include examining three specific program topics: behavior change, free distribution and public-private partnerships.

Behavior Change

The *Tubeho Neza* program uses theories of behavior change such as diffusion of innovation and the health based model with both health based messaging as well as economic and social messaging to promote behavior change.

Diffusion of Innovation (DOI) theory outlines communication stages over time which technology adopters go through as well as outlines categories of adopters. The *Tubeho Neza* program uses DOI theory as model for individual household level adoption[30]. The Health Belief (HB) model is also used, whereby a health threat is recognized by the individual[31]. The HB model is extensively used throughout the *Tubeho Neza* program's educational messaging to relate health outcomes to clean drinking water and clean indoor air. Similarly important in creating behavior change are expressing non-health benefits to users. Previous interventions related to both water quality and improved cookstoves emphasize the need to highlight non-health benefits such as those related to economic and social benefits[24,32,33].

Free Distribution

The *Tubeho Neza* program includes the free distribution of the water filter and cookstove. A highly discussed topic in program design revolves around the free distribution of products in public health programs. Recent studies have examined cost-sharing for bed-nets, cook-stoves and water treatment systems and have found that there is no correlation between free distributions and low adoption rates[34]. Meanwhile, a study examining point-of-use chlorination through marketing campaigns and coupon schemes found these to be ineffective strategies but found free chlorination dispensed at water sources along with community providers as the most effective strategy in potentially preventing diarrheal incidence in areas like rural Kenya[35]. Furthermore, Bensch and Peters determined that a free stove program in Senegal resulted in high uptake of almost 100% of households[36].

Public-Private Partnerships

Rwanda relies both on direct donor funding to government programs, as well as careful coordination of programs managed by international non-profits and health sector businesses. In 2002, the government provided funds for only a quarter of the total health care costs, the remainder covered by donors and private sources[37]. Donation based non-profits are not providing services to the target populations serviced by the *Tubeho Neza* program. The carbon credit business model used to partially finance the *Tubeho Neza* program, is designed to recuperate invested costs by the generation and sale of carbon credits associated with the proportion of the intervention that continues to demonstrate successful behavior change.

Study Three: *Evaluation of a Large Scale Water Filter and Improved Cookstove Distribution in Rwanda: A Cost-Benefit Analysis of Livelihood and Environmental Impacts*

The primary method for evaluating sustainability of the program is a cost benefit analysis. Previous studies have reported a cost benefit ratio (CBR) which can be used to compare the program to other possible interventions or previously implemented programs. An evaluation which modeled reducing by half the world's population without an improved cooking stove, found a CBR of around 60 with fuel savings alone offsetting the cost of the intervention[13]. CBRs evaluating improved cookstove programs in Uganda[15], Malawi[16] and Mexico[14] ranged from 3 to 29. While three out of the four studies included the addition of health benefits, which will not be analyzed in this study, all reported fuelwood savings accounting for over half of the value of the program benefits and, with the exception of the study conducted in Mexico, time savings greatly outweighing health benefits. A cost benefit analysis of global interventions in the water supply and sanitation sector reported CBRs from 4 to 32, for the scenario of halving the proportion of people who do not have access to an improved water source, and CBRs of 5 to 41 when providing universal basic access to improved water and sanitation as well as point of use water treatment through use of chlorine. Additionally while this study also included benefits related to health, time savings from improved accessibility dominated health benefits by greater than 3 to 1[38].

Study Four: *Assessing Improved Cookstove Sustainability: An Evaluation of Locally Manufactured and Imported High Efficiency Rocket Stoves in Rwanda*

An important decision and often highly debated topic in cookstove programs is whether to import cookstoves or make them locally. No similar studies could be found which specifically compared these two stove types. However a study which compared the sustainability of ceramic point-of-use water filters and community drinking water systems was used as a model for this study including similar metrics for environmental, social and economic sustainability. Specifically a life cycle assessment approach was used to evaluate environmental sustainability, health based metrics were used to evaluate social sustainability and cost effectiveness was used to evaluate economic sustainability. While a full sustainability study on any improved cookstove was not found, a recent study examining the life cycle cost of an imported stove, the Berkeley-Darfur, was published. The study primarily concluded that use phase emissions, at least related to green-house gas emissions, far outweighed any emissions during the production of the cookstoves.

Study 1: Designing and Piloting a Program to Provide Water Filters and Improved Cookstoves in Rwanda

Barstow CK, Ngabo F, Rosa G, Majorin F, Boisson S, Clasen T, and Thomas EA. (2014) Designing and Piloting a Program to Provide Water Filters and Improved Cookstoves in Rwanda. PLoS ONE 9(3); e92403. Doi:10.1371/journal.pone.0092403

Abstract

Background

In environmental health interventions addressing water and indoor air quality, multiple determinants contribute to adoption. These may include technology selection, technology distribution and education methods, community engagement with behavior change, and duration and magnitude of implementer engagement. In Rwanda, while the country has the fastest annual reduction in child mortality in the world, the population is still exposed to a disease burden associated with environmental health challenges. Rwanda relies both on direct donor funding and coordination of programs managed by international non-profits and health sector businesses working on these challenges.

Methods and Findings

This paper describes the design, implementation and outcomes of a pilot program in 1,943 households across 15 villages in the western province of Rwanda to distribute and monitor the use of household water filters and improved cookstoves. Three key program design criteria include a.) an investment in behavior change messaging and monitoring through community health workers, b.) free distributions to encourage community-wide engagement, and c.) a

private-public partnership incentivized by a business model designed to encourage “pay for performance”. Over a 5-month period of rigorous monitoring, reported uptake was maintained at greater than 90% for both technologies, although exclusive use of the stove was reported in only 28.5% of households and reported water volume was 1.27 liters per person per day. On-going qualitative monitoring suggest maintenance of comparable adoption rates through at least 16 months after the intervention.

Conclusion

High uptake and sustained adoption of a water filter and improved cookstove was measured over a five-month period with indications of continued comparable adoption 16 months after the intervention. The design attributes applied by the implementers may be sufficient in a longer term. In particular, sustained and comprehensive engagement by the program implementer is enabled by a pay-for-performance business model that rewards sustained behavior change.

Introduction

Access to improved drinking water and clean burning stoves could benefit the millions who suffer from diarrheal disease and pneumonia, two of the leading causes of death around the world for children under five. Worldwide, of the 7.6 million deaths in children under 5 in 2010, 64% were associated with infectious diseases including 18% with pneumonia and 11% with diarrhea. Combined, pneumonia and diarrhea kill over 2 million children each year[1].

Some of these deaths may be avoided through interventions to improve indoor air quality and household water quality: pneumonia is often linked to indoor air pollution from biomass fuels[5,6] and diarrhea to deficiencies in water and sanitation, including poor water quality[4]. Many cookstove interventions have shown a reduction in indoor air pollutants such as carbon monoxide and fine particulate matter[9,10]. Similarly, interventions targeted at improving household water quality through the implementation of water treatment strategies such as chemical treatment, boiling, solar disinfection or filtration have been shown to reduce diarrheal disease[7,8].

Even with the fastest annual reduction in child mortality in the world, the Republic of Rwanda still faces challenges related to pneumonia and diarrhea: among deaths of children under 5, pneumonia accounts for 18% and diarrhea for 8%[17]. Cooking practices in a rural Rwandan household may contribute to this pneumonia burden since the predominate fuel and cookstove pairing is wood on a three stone fire[19]. Additionally, while Rwanda has demonstrated significant progress towards the Millennium Development Goals, almost 30% of households do not have access to an improved water source[18], and the improved water sources may become contaminated during collection, transport or storage within the home[39,40]. Once water is in the households, less than half (46.1%) of rural Rwandan families report treating their drinking water, with boiling as the leading treatment method (38.1%)[18], which again can become recontaminated after treatment[39]. The Rwanda Standard for Potable Water states that the microbiological limits for potable water for total CFU/100 ml of total coliforms should be 0[41]. A baseline water quality assessment of 230 improved water sources, 78 unimproved water sources, and stored water in 468 households across all 30 districts in Rwanda indicated that 27.8% of improved water sources, 80.2% of unimproved water sources, and 58.3% of stored household water supplies exceed this standard[42], falling into the “intermediate”, “high” or “very high” risk World Health Organization categories[43] for biological contamination of drinking water supplies. Another study of households within the other 11 districts of the project area prior to the start of the program implementation indicated that 81.1% of households exceed this standard, with 59.1% falling into the “intermediate” or “high” risk categories[44].

DelAgua Health, a for-profit social enterprise, was established to combine household technologies that address environmental health issues with market-based mechanisms. DelAgua Health participates in the United Nations Clean Development Mechanism (CDM) to earn carbon credits associated with the reduced use of, and demand for, fuel wood associated with water treatment and cooking, and then sell those credits to buyers as a way to recover costs and profit[45].

Carbon finance markets facilitate the reduction of greenhouse gas emissions worldwide through economic incentives, while allowing cleaner economic development to take place. Each emission reduction credit represents the non-emission of one tonne of carbon dioxide into the atmosphere. The carbon credits generated under the CDM help Kyoto Protocol Annex I countries to meet their binding targets, and can be traded in the marketplace. However, the carbon markets have yet to be well utilized to finance the distribution of humanitarian technologies in the least developed countries, particularly in Africa. Although the CDM is a multi-billion dollar industry, fewer than 2 percent of projects are registered in African nations[46].

Depending on the project location, structure, methodology and registration mechanism employed, a water treatment and/or cookstove program can earn between approximately 1/2 and 5 carbon credits per household, per year. The carbon credits earned are a function of the approved methodology, referenced to a baseline condition and the current performance of the program, as audited by independent firms. The reported reductions are then issued by the registration authority and are then sold to buyers. Carbon credit buyers may be banks, energy companies, brokers, or sovereign nations who require credits for either regulatory compliance or voluntary social responsibility efforts, or both. Because the carbon credits are issued in proportion to the present adoption and proper use of intervention technologies, this encourages sustained engagement by the program implementer and creates a pay-for-performance model.

In Rwanda, DelAgua Health is partnered with the Ministry of Health since 2012 to distribute free of charge household water treatment and high efficiency cookstoves to approximately 600,000 households (about 3 million people), throughout the country's 30 districts. The project will target *Ubudehe* categories 1 and 2, the government-recognized poorest 30% of the country. *Ubudehe* category is determined by community members based on classifications outlined by the Rwandan Ministry of Local Government[47]. Households categorized as *Ubudehe* 1 and 2 already receive free medical and other assistance through government programs.

A pilot program was initiated in October 2012 to provide input for the full effort, scheduled to start in mid-2014. This pilot was conducted after findings from a preliminary study of 100 households in July 2012. This effort was judged by the implementers to be sufficiently promising for testing at a larger scale. This paper discusses the design, development, implementation, monitoring and periodic modification of the October 2012 pilot program. We summarize the results of surveys collected to evaluate key outputs including intervention uptake and use. Other aspects of the pilot are described elsewhere, including a novel method for assessing intervention use with remotely reporting sensors[48] and a randomized controlled trial to study the impact of the intervention on drinking water quality and household air pollution[49].

Materials and Methods

Design Objectives

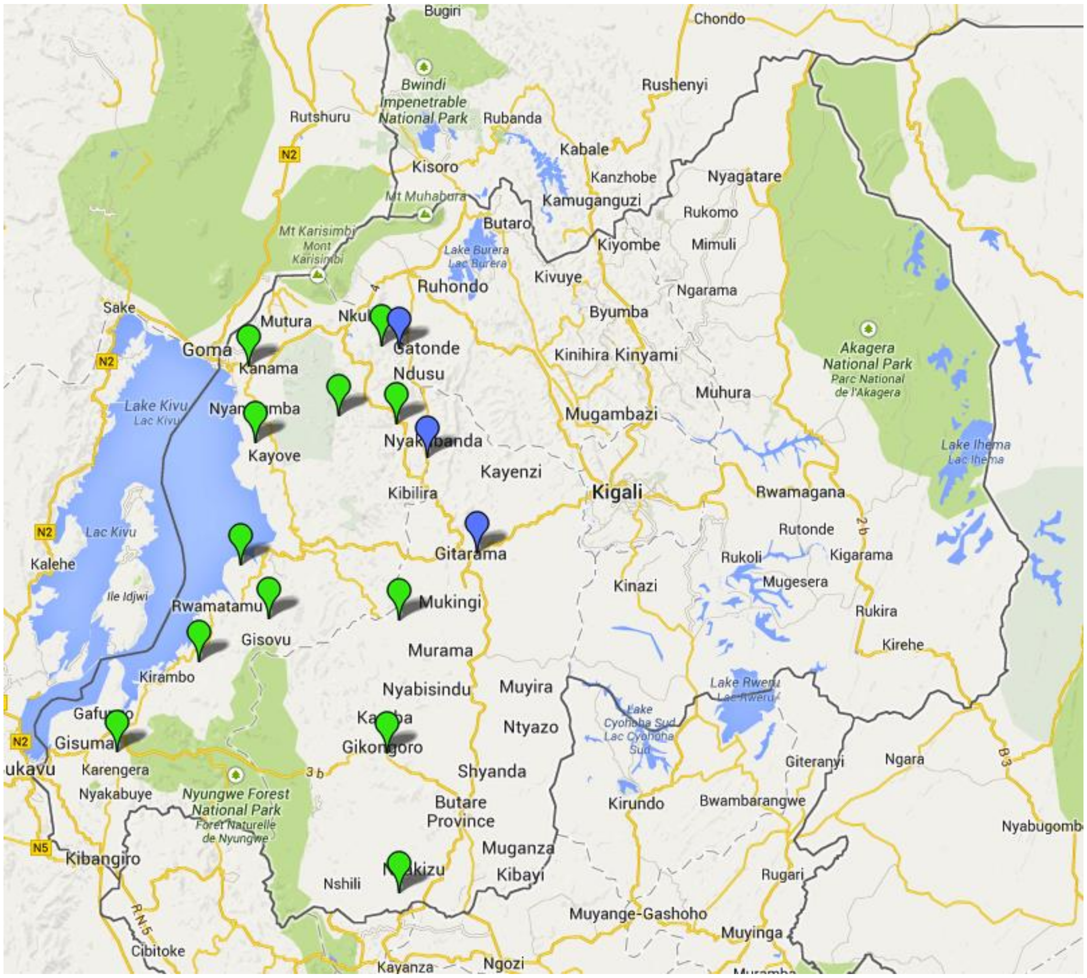
The objective of this study was to identify if certain design criteria, integrated together and applied to environmental health technologies, could result in a meaningful proportion of continued use of stoves and water filters. These design attributes are evaluated as a whole, though estimates of relative value are provided in the discussion. The three program design choices considered fundamental were:

1. *Free Distribution*: Free provisioning of high quality stoves and water filters under the authority of the Government of Rwanda and through established community mechanisms including community meetings and community leadership.
2. *Behaviour Change*: A behaviour change messaging and monitoring effort that prioritizes consistent and correct adoption of the stoves and filters through community and household level activities, focusing on both health and non-health benefits.
3. *"Pay for Performance" Public-Private Partnership*: A public-private partnership with the Rwanda Ministry of Health enabled by anticipated carbon credit revenues, which allows sustained, comprehensive community engagement by virtue of future anticipated "pay for performance" carbon credit revenues.

Program Setting and Population

The pilot was conducted in a convenience sample of 15 non-randomly selected villages spread across 11 districts in Western Rwanda (Figure 1). The 15 villages were selected to have at least one village per the 11 districts and the remaining four villages in districts with the largest populations. Additional inclusion criteria included ensuring that no villages were in adjacent sectors (district subdivisions), less than 20% of households in each village served by piped water; less than 60% of households in each village using any water treatment other than boiling; less than 20% of households in each village using cooking fuel sources other than biomass or charcoal; and less than 20% of households in each village using any stove other than a 3-stone fire or two other locally made unimproved stoves (known as *Rondereza* and *Imbabura* stoves). These inclusion criteria were selected by program staff to be representative of typical rural villages in Rwanda, based on rural water service and energy use characteristics identified in the Rwanda 2011 Demographic and Health Survey. Program staff visited each candidate village in advance to confirm with village officials that it met eligibility criteria. All 1,943 households who were registered as members of the 15 villages were eligible to participate in the study. While the full program will consist of distribution to only *Ubudehe* 1 and 2 households, this pilot program consisted of all households, of any *Ubudehe* category, in the 15 villages. The full program originally consisted of distribution to all households in the Western province of Rwanda but was later revised to be a country wide program of *Ubudehe* 1 and 2 households. This program change was directed by the Government of Rwanda Ministry of Health.

Figure 1. Program villages. RCT villages shown with blue pins.



Intervention Hardware

The water filter used in this program, the Vestergaard Frandsen LifeStraw Family 2.0 is a point-of-use microbial water treatment system intended for routine use in low-income settings. The system is a table-top unit where the user pours untreated water through a 20 micron pre-filter into a six liter influent water tank. Water is then gravity-filtered through a 0.20 micron hollow-fiber ultrafiltration membrane into a 5.5 liter safe storage container. Water can be dispensed from the safe storage container through a plastic tap, limiting recontamination. The filter is backwashed by squeezing a plastic bulb located on the opposite side of the tap. The membrane can filter up to

18,000 liters of water[50], enough to supply a family of five with microbiologically clean drinking water for three to five years. The system exceeds the ‘highly protective’ World Health Organization Standard for household water treatment technologies[51,52]. In a recent study, an earlier version of this filter was shown to be highly effective in improving water quality and was protective against diarrhea among HIV positive individuals, reducing longitudinal prevalence by over 50%[12].

The cookstove used in this program, the EcoZoom Dura, is based on the rocket-stove concept that is designed to concentrate the combustion process while channeling air flow to create a more complete burn. A complete burn of carbon rich material will also result in little to no smoke. Included with the stove are a “stick support” on which fuelwood is placed to promote air flow and a “pot skirt” which increases thermal efficiency. In the field, performance is variable but when properly used, a rocket stove will significantly reduce fuelwood use by at least 50%, although reductions in indoor air pollution vary between designs, fuel types and use[53]. The thermal efficiency of this stove is 38%[54].

Intervention Design

The program is designed leveraging established behavior change theories, including the Diffusion of Innovation theory[30] and the Health Belief Model (HBM)[31]. In particular, the program design assumes that continued, comprehensive engagement is critical in order to effect positive behavior change. The program design takes a hybrid approach, integrating pieces of these theories that apply in a Rwandan context to shape the communication strategy of the program.

Several components of the diffusion of innovation theory are applied to the program. At the initial distribution meeting, community members are informed about the potential health and other benefits of the water filter and cookstove creating ‘initial knowledge’ around the technologies. The ‘persuasion stage’ is initiated through demonstrations at both the community meeting and the household. The stove demonstration includes assembling the stove, how to adjust a pot skirt which can be fitted to different sized pots and finally a fire being started in the stove with some demonstrations including boiling a pot of water to show the rapidity of the cooking process. The water filter includes a demonstration of filtering visually dirty water with clear water coming out of the tap and the maintenance procedure, which includes backwashing the filter. Progressing to the ‘decision stage’ the household is then asked to demonstrate use and maintenance of the technology, allowing them to trial the technology. Households then move into the ‘implementation stage’ where they can choose to adopt or reject the technology. About a month later, the program implements the ‘confirmation stage’ where households who have chosen to partially adopt or reject the technology are given additional training and messaging to hopefully reverse their decision.

Village chiefs are promoted as ‘early adopters’ because of their high degree of influence and respect within their villages. In this program the change agents are Community Health Workers (CHWs). The CHW system in Rwanda includes three CHWs per village who are part-time volunteers of sector health centers and are compensated with a stipend. They provide basic services such as maternal and newborn health monitoring, vaccination advocacy, family planning, treatment of malaria, and sanitation and hygiene education. Through this program CHWs play several important roles including informing households of the need for the devices, encouraging adoption and analyzing potential problems with the technologies. The CHWs play an especially important role with the ‘late adopters’ and ‘laggards’ as more effort is needed to change the household’s old habit and promote the new behaviors[32].

The Health Belief Model is used to shape messaging. The belief that there is a health threat is compelled by messaging related to clean drinking water and clean indoor air. Households are educated about the reduced risk of diarrheal disease from water borne diseases and the reduced risk of respiratory problems from breathing indoor air pollutants. Additionally an important concept in social cognitive theory is often added to the health belief model, self-efficacy, which states that the user must believe that they can adopt the new behavior[33]. This is facilitated through households gaining confidence in the use of the technologies by having members of the household demonstrate proper use.

While the health belief model provides relevant guidance on behavior change theory it is important that the program also express non-health benefits to users. Previous interventions related to both water quality and improved cookstoves emphasize the need to highlight non-health benefits such as those related to economic and social benefits[24,32]. Thus CHWs educate households on additional benefits such as reduction in medical costs from the water filter and a reduction in cooking time and expenditure on fuel costs for the cookstove.

Adoption and Monitoring Survey

Households were assigned to receive the adoption and monitoring survey in one of six rounds by a random number generator. Approximately 325 households were surveyed each month with the exception of month five where approximately twice as many households were surveyed as rounds 5 and 6 were combined because of time constraints. Environmental Health Officers (EHOs) were responsible for conducting the surveys. Environmental Health Officers (EHOs) are full time employees of the Ministry of Health at sector health centers who are responsible for a range of health interventions, including, food safety, waste management, water, sanitation and hygiene inspection, indoor air pollution and environmental emergency health interventions[47]. Each household was surveyed by EHOs only once during the five month period.

The survey consisted of about 100 questions and was administered using a smartphone in Kinyarwanda by an EHO. Information included household identifying information, demographics, cooking practices, and water treatment and collection practices. The survey included both self-reported use questions to be answered by members of households and observational questions which EHOs answered based on their observations. Observational use of the water filter was measured by checking if water was present in the filter at the time of the visit while observational use of the stove was only confirmed if the stove was actually being used at the time of the visit.

Survey Data Analysis

All survey data was uploaded to the doForms database where it was analyzed using T-SQL and R-Project. Only surveys that fell within 15 to 90 minute survey duration were included in the analysis. All numerical outcomes were additionally analyzed using an outlier analysis where only 1.5 times the upper and lower interquartile range were included in that particular outcome. This outlier exclusion was chosen to be consistent with the program's carbon credit monitoring requirements[55]. Analysis of variance was used to compare group means. Additionally any missing data was excluded from the analysis.

Focus Group Discussions

Three focus group meetings were conducted concurrently with EHOs and CHWs to assess qualitative aspects of the program. A total of 30 participants attended the meetings including one CHW from each of the pilot villages and all EHOs. CHWs were chosen by DelAgua staff as the highest performing CHWs within each village. Topics covered included perceived adoption of technologies within their villages, problems with filter and stove hardware, effectiveness of household messaging and boundaries to exclusive adoption of the filter and stove.

Ethics and Consent

The study was reviewed and approved by the Rwanda National Ethics Committee (IRB #328/RNEC/2012), University of Colorado Institutional Review Board (Protocol #12-0564), and the London School of Hygiene and Tropical Medicine Ethics Committee (Trial registration: Clinicaltrials.gov NCT01882777). Each participating household gave informed, verbal consent after having received complete details regarding the purpose of the survey as well as information regarding privacy of personal information. Enumerators were required to confirm electronically, on their smartphone surveys, if a.) the respondent was over 18, and b.) if they gave verbal consent, before the smartphone allowed the survey to continue. These consent records are kept on a password protected server. Verbal consent was requested and approved by the approving ethics committees, based on the high percentage of illiteracy within the study population. Rwandan residents are often asked about their water and energy habits by community health workers, and the signing of a document adds a level or formality that may mislead participants. Participants were given the opportunity to ask any questions before agreeing to participate. All households were entitled to retain their filters and stoves at the conclusion of the study.Participation in the study was not a prerequisite to receiving the filters and stoves.

Results

Program Delivery

All households that were registered in the 15 villages according to the village chief's list were distributed a stove and filter. The model of distributing at a central location allowed for the implementer to transport the technologies to a location that could be reached by vehicles of which many households could not. It was then members of the household's responsibility to get the stove and filter to their homes.

Household Characteristics

A total of 1943 households participated in the study, from which 1634 (84.1%) valid surveys were included in the analysis. Selected household characteristics are summarized in Table 1. The mean household size was 4.55, consistent with Rwanda's 2011 Demographic and Health Survey household size of 4.5. Approximately one-third (29.3%) of households reported being categorized as *Ubudehe* 1 or 2, 70.5% were classified as 3 or 4 and 0.2% as *Ubudehe* 5 or 6. *Ubudehe* 1 and 2 household size was significantly lower than the entire study population with 3.85 persons per household. However, fuel type and water source were similar with the majority of all households (92.4%) and *Ubudehe* 1 and 2 households (89.1%) using wood as their primary fuel source and all households (41.1%) and *Ubudehe* 1 and 2 households (42.9%) reporting a public tap as their primary drinking water source.

Table 1. Selected demographics and characteristics regarding water and energy practices.

	All households		***Ubudehe* 1 and 2**	
	N	%	N	%
Number of Households	1634		478	
Household size, mean (95%CI)	4.55 (4.46-4.65)		3.85 (3.70-4.00)	
***Ubudehe* Category**				
1 or 2	478	29.3%		
3 or 4	1152	70.5%		
5 or 6	4	0.2%		
Fuel Type				
Wood	1510	92.4%	426	89.1%
Straw/Shrubs/Grass	93	6.3%	42	8.8%
Charcoal	28	1.9%	10	2.1%
LPG/Natural Gas/Biogas	1	0.1%	0	0.0%
Other	2	0.1%	0	0.0%
Drinking water source*	1576		457	
Public Tap	647	41.1%	196	42.9%
Protected Spring	592	37.6%	149	32.6%
Unprotected Spring	184	11.7%	62	13.6%
Surface Water	56	3.6%	26	5.7%
Hand Pump	37	2.3%	6	1.3%
Piped Water in Home	31	2.0%	8	1.8%
Unprotected Well	24	1.5%	8	1.8%
Protected Well	4	0.3%	1	0.2%
Rainwater	1	0.1%	1	0.2%

*Missing 58 (3.6%) answers

Filter Adoption and Use

Adoption of the LifeStraw filter was measured at approximately 90% or greater by several metrics. Households reported use of the filter had the highest adoption rate with 96.5% of households reporting the water filter as the treatment method for the last water they drank. An observational measure of use through presence of water in the filter showed a slightly lower adoption rate with 9 out of 10 households having water in their filter at the time of household visit (Table 2). Similar adoption rates as measured observationally were seen over the five follow up visits with the first follow up visit having the highest adoption rate of 92.6% and the lowest adoption rate reported as 86.4%. No longitudinal trend in adoption was observed through the five months of the study.

Adoption rates were further analyzed to understand any differences between all households in the study and those who were identified as *Ubudehe* 1 and 2 as well as any differences across the 15 villages. *Ubudehe* 1 and 2 adoption rates were similar to those seen by the full program with an *Ubudehe* 1 and 2 reported adoption rate of 95.6% and an observational adoption rate of 88.5% (Table 2). Observed filter adoption across all 15 villages varied between 74.5% and 98.1% (Table 3) with the lowest adoption rate occurring in one village (Mara) by almost 10% below all other villages. This is likely due to rodents destroying the filter tubes with 21.8% of filter repair of this problem in this village.

Table 2. Primary filter adoption and use outcomes.

	All households				*Ubudehe* 1 and 2			
	N	%	Mean (95% CI)	ANOVA p-value	N	%	Mean (95% CI)	ANOVA p-value
Reported Filter Use	1576	96.5%			457	95.6%		
Observed Filter Use	1471	90.0%			423	88.5%		
Other Purposes for Filtered Water	201	12.8%			74			
Cooking	57	28.4%			24	32.4%		
Hand Washing	57	28.4%			20	27.0%		
Washing Dishes	55	27.4%			18	24.3%		
Other	32	15.9%			12	16.2%		
Cleaning Frequency	1576				457			
Everytime	1004	63.7%			265	58.0%		
Daily	234	14.8%			71	15.5%		
Every Other Day	53	3.4%			20	4.4%		
2 Times per Week	236	15.0%			83	18.2%		
Once per Week	48	3.0%			18	3.9%		
Once per Month	1	0.1%			0	0.0%		
Liters per household per day	1210*		5.06 (4.99-5.12)	0.193	304*		5.11 (5.04-5.18)	0.194
Liters per person per day	1436*		1.27 (1.25-1.29)	0.090	304*		1.11 (1.10-1.13)	0.194

*Only records within 1.5 IQR were included

Table 3. Filter and stove use by village.

	Observed Filter Use			Cooking on EcoZoom only at time of visit		
Village	Valid observations	N	%	Valid observations	N	%
Mara	110	82	74.5%	35	24	68.6%
Kigaga	90	82	91.1%	23	19	82.6%
Buhunde	117	103	88.0%	31	11	35.5%
Rushishi	147	137	93.2%	26	15	57.7%
Nyarubuye	116	102	87.9%	16	10	62.5%
Karambo	177	149	84.2%	34	23	67.6%
Rubona	65	62	95.4%	21	13	61.9%
Burorero	214	191	89.3%	18	7	38.9%
Nyabivumu	61	58	95.1%	22	22	100.0%
Rambura	116	107	92.2%	12	6	50.0%
Kabuga	111	106	95.5%	23	9	39.1%
Rupango	106	102	96.2%	31	27	87.1%
Gisoro	54	53	98.1%	8	3	37.5%
Nyarutovu	81	77	95.1%	31	21	67.7%
Gasumo	69	60	87.0%	11	8	72.7%
All villages	1634	1471	90.0%	342	218	63.7%

Households reported treating an average of 5.06 liters per day in all households and 5.11 liters per day in *Ubudehe* 1 and 2 households with no significant difference between monthly survey rounds. This equates to an average of 1.27 liters per person per day for all households and 1.11 liters per person for *Ubudehe* 1 and 2 households, possibly because of the smaller household sizes (Table 2). Regardless, water quantity consumption is lower than advised by CHWs at 2 liters per person per day. Similar consumption rates of 1 to 1.5 liters per person per day were reported at focus group discussions conducted with community health workers. Primary reasons discussed at the focus group for not consuming more water included not having a container to carry water when leaving the household, an inability to drink 2 liters per day, and a preference for drinking other beverages.

12.8% of households that reported using the filter also reported doing so for purposes other than drinking water. The most common uses were cooking (28.4%), hand washing (28.4%) and washing dishes (27.4%) (Table 2).

Almost two thirds (63.7%) of households reported backwashing their filter every time they treated water as advised in the household visit (Table 2). Not backwashing the filter frequently enough may be the cause of the most common reported problem with the filter, which was that it was clogged and wouldn't filter water (N=45). The next most common problem reported was damage to rubber tubes because of rodents (N=33). Overall 11.1% of households over the 5-month period reported any problems with the filter during the household visits. 57 (2.9%) filters were replaced and 366 (18.8%) filters were repaired with the same primary reported problems of tubes being damaged by rodents (N=119) and filter clogged (N=124) (Table 4).

Table 4. Reasons for stove and filter problems, repairs and replacements.

	N	%
Reported reasons for not using EcoZoom	168	
Don't have dry wood	46	27.4%
Difficult to use	31	18.5%
Doesn't warm the house	20	11.9%
Use of a different fuel	13	7.7%
Other (20)	76	45.2%
Reported stove problems	73	
Pot skirt missing screw	22	30.1%
Pot skirt damaged	8	11.0%
Stove too small	6	8.2%
Difficulty in moving pot skirt to another pot	6	8.2%
Ceramic chamber cracked	4	5.5%
Stick support damaged	4	5.5%
Other (12)	23	31.5%
Reported reasons for continued use of old stove	1386	
More than one stove needed	649	46.8%
Don't have dry wood	330	23.8%
Need to warm house	126	9.1%
Pot is too big for stove	73	5.3%
Other (28)	208	15.0%
Reasons for stove repair	67	
Skirt replaced/Skirt damaged	48	71.6%
Skirt replaced/adjustment screws missing	11	16.4%
Stick support replaced/Broken	3	4.5%
Stick support replaced/Missing	1	1.5%
Other	4	6.0%
Reported filter problems	182	
Filter broken or clogged	45	24.7%
Tubes damaged/eaten by rodents	33	18.1%
Tubes are kinked	26	14.3%
Difficulty in backwashing	22	12.1%
Tap is leaking or broken	18	9.9%
Backwash bulb is damaged	17	9.3%
Other (6)	21	11.5%
Reasons for filter repair*	391	
Filter cartridge clogged	124	31.7%
Tubes replaced from rodent damage	119	30.4%
Backwash water not going into container	62	15.9%
Broken tap handle	39	10.0%
Broken tap - leaking	10	2.6%
Backwash leaking	5	1.3%
Backwash bulb replaced	2	0.5%
Other	30	7.7%

*366 total filters repaired - 25 had multiple problems

The majority of filter problems were addressed through repair and replacement by program staff. Households contacted program staff through phone numbers on informational posters which were provided during the initial household visits. Common repairs included replacing tubes eaten by rodents or power backwashing the filters using a hand pump pressurized canister.

Stove Adoption and Use

As seen with filter adoption, reported primary use of the EcoZoom stove was around 90% for the entire population and *Ubudehe* 1 and 2 households (Table 5). Primary reasons given for stove adoption during focus group meetings included cost savings, time savings and cleanliness of the cook and kitchen when using the EcoZoom. However, 71.5% of these households reported continuing to use their traditional stove as well as their EcoZoom stove. Of households cooking at the time of the follow up visit (20.9%), about two thirds (63.7%) were using the EcoZoom stove, 21.9% a traditional 3-stone fire, and 11.4% cooking on a different traditional stove. Ten households (2.9%) were also observed using both the EcoZoom stove and a traditional stove.

Table 5. Primary stove adoption and use outcomes.

	All households				*Ubudehe* 1 and 2			
	N	%	Mean (95% CI)	ANOVA p-value	N	%	Mean (95% CI)	ANOVA p-value
Reported Primary Stove Use	1634				478			
EcoZoom	1479	90.5%			430	90.0%		
Traditional 3-stone Fire	68	4.2%			23	4.8%		
Other Traditional Stove	78	4.8%			22	4.6%		
Other Stove	9	0.6%			3	0.6%		
Stove Using at Time of Visit	342	20.9%			110	23.0%		
EcoZoom Only	218	63.7%			70	63.6%		
Traditional 3-Stone Fire	75	21.9%			28	25.5%		
Other Tradional Stove	39	11.4%			11	10.0%		
EcoZoom and Other Stove	10	2.9%			1	0.9%		
Cooking Location at Time of Visit								
Outdoor	145	42.4%			41	37.3%		
Indoor	123	36.0%			49	44.5%		
Separate Kitchen	74	21.6%			20	18.2%		
Continuing to Use Old Stove	1169	71.5%			316	66.1%		
# of EcoZoom uses per week	1517*		1.37 (1.34-1.40)	<0.000001	438*		1.38 (1.32-1.44)	0.869
% EcoZoom Use	1625*		71.2% (69.8%-72.7%)	0.052	474*		73.7% (71.0%-76.4%)	0.896
% Wood Reduction	1551*		65.8% (65.0%-66.6%)	0.593	443*		65.9% (64.3%-67.4%)	0.082

*Only records within 1.5 IQR were included

Using the same metric of observed cooking use, EcoZoom use at the time of the household visit varied from 35.5% - 100.0% across the 15 pilot villages though the sample sizes were low in some villages with only 342 total observed cooking events. The three villages with the lowest observed use were Buhunde, Gisoro and Burorero (Table 3).

The two primary reasons reported during household surveying for not using the EcoZoom stove were inability to use wet wood in the EcoZoom stove (N=46) and difficulty in using the stove (N=31). This reported difficulty may refer to the required increased frequency of fire tending while cooking on the EcoZoom stove as 67.1% of households reporting tending the fire more with the EcoZoom stove than with their old stove (Table 4). Additionally the food most frequently reported cooked was beans (53.9%), requiring cooks to tend the fire frequently over a long period of time. Focus group discussions further emphasized these problems with the primary reasons for not using the stove as high frequency of fire tending, difficulty in burning wet wood when dry wood was unavailable and the inability to warm the house. Tending the fire was expressed most frequently as the primary issue since cooks use smaller pieces of wood to keep the fire going.

To assess the degree of EcoZoom stove use compared to other traditional stoves, households were asked the number of times per week they used each stove in their home. The EcoZoom stove was reported being used on average 1.37 times per day for 71.2% of cooking events in a household with a significant difference between monthly survey rounds (Table 5).

Primary reasons for continued use of a traditional stove included needing more than one stove at a time (N=649) and the inability to cook on the EcoZoom stove when only wet wood was available (N=330) (Table 4).

Cooking location was assessed because of the program emphasis on cooking outdoors during education and training activities. 342 observations of cooking location at the time of follow up visit were made, where 42.4% were cooking outdoors, 36.0% were cooking indoors and 21.6% in a separate kitchen. Slightly higher rates of cooking indoors were observed in the *Ubudehe* 1 and 2 households with 37.3% cooking outdoors, 44.5% cooking indoors, and 18.2% cooking in a separate kitchen (Table 5).

To quantify wood savings households were asked to report the number of wood bundles they collected or purchased before and after receiving the EcoZoom stove. Of the 1551 valid responses, an average wood reduction of 65.8% was reported across all rounds with no significant difference between the five rounds (Table 5).

A total of 73 stove problems were reported with the two most common problems being the pot skirt screw missing (N=22) and the pot skirt degrading (N=8). These were also the two most common reasons for stove repair with 48 pot skirts (2.5%) being replaced due to melting and 11 pot skirt replacements due to missing adjustment screws (Table 4). No stoves were replaced during the five months following distribution.

Discussion and Conclusions

In the pilot program described here high levels of uptake and continued use of water filters and improved cookstoves were found. The rigorous five-month follow up study was complemented by qualitative assessments by the implementation team periodically over an additional 11 months. 16 months after the intervention, adoption rates of the water filters and cookstoves were assessed to being comparable to those observed during the detailed 5-month study. This outcome may be described through the three design choices outlined previously. These design choices are intended to be applied in the full-scale program scheduled for deployment in 2014 and 2015. A key design difference in the planned full-scale program is that it will reach only the poorest households in a given village.

Behavior Change

The primary purpose of the technologies provided is to realize a health benefit. As a first step, communicating these potential health benefits to a user is often seen as an appropriate prerequisite to adoption. A lack of knowledge of potential health benefits has been shown to result in poor adoption of products like stoves and filters[56]. It has also been demonstrated that knowledge of health benefits alone is not sufficient to result in sustained behavior change in an individual or household[24]. The program studied here uses theories of behavior change such as diffusion of innovation and the health based model with both health based messaging as well as economic and social messaging to promote behavior change within the program.

In the case of the filter, adoption was measured around 90% for the five months of the study. A high adoption outcome has been seen previously with earlier versions of the LifeStraw Family filter with 96% adoption in Zambia[12] after 12 months and 68% adoption in the Democratic Republic of Congo after eight months[21]. Additionally, compared to other point-of-use water methods, filtration often has higher adoption rates[22] possibly because it is seen as easier to use [39] and doesn't result in a change in taste and odor[24]. However, while adoption of the filter was high, the recommended water consumption of 2 liters per person per day was not reached in most cases, suggesting that households may be drinking untreated water at times, a behavior also seen in the study conducted in the Democratic Republic of Congo[21]. Even occasional consumption of untreated water can greatly reduce the potential health benefits from water quality interventions[25,26]. Reasons that households gave for not exclusively drinking clean water included not having clean water when they were away from home and not having any filtered water at the time they were thirsty. Similar reasoning has been found in other studies where water treatment needed to be integrated into the everyday lifestyle of the family[24]. However, guidance from the existing literature is limited to help guide behavior change program development[57] so additional qualitative research is needed to understand people's behavior and preferences for exclusive drinking of treated water to adjust messaging and education activities to be more effective. In collaboration with the manufacturer, the product has been updated based on recipient feedback to protect the soft tubes and the backwash bulb, and to allow for a separable safe water storage container for ease of cleaning.

Adoption of the stove was also around 90%. Non-health benefits such as a cleaner appearance and cooking environment were more highly valued than health or environmental impacts, as observed in other studies. Exclusive use of the EcoZoom stove was only reported in 28.5% of households with most continuing to use their old stove with the EcoZoom stove. The earliest models for stove adoption assumed a "fuel switch" wherein behavior is switched over a short period of time from one stove/fuel combination to another. More recently, continued "stove stacking", where the use of multiple stoves for varying purposes, has been shown to be a more stable behavior, and can result in as high as 90% of stove usage events on the improved stove[58]. Studies have shown that households do not move from older existing methods of cooking such as a 3-stone fire to exclusive use of an improved stove. In order to realize the potential health benefits of improved stoves, exclusive use will need to be further promoted within the program[27–29]. Working with the stove manufacturer, the pot skirt has been updated to reduce degradation.

This stove stacking behavior suggests that the true innovation being introduced is not necessarily the stove itself, but the modified cooking practices required to realize the health and other benefits. Previous studies have found that an improved stove must meet the user's traditional cooking needs in order for adoption to occur. The primary barriers to adoption or exclusive use of the EcoZoom stove in this study center around modifying current practices such as additional fire tending. While the EcoZoom stove is likely to decrease the cooking time of an individual cooking event, additional fire tending compared to a traditional 3-stone fire is often necessary, as reported in the focus group convened for this study. There may be an increased emissions exposure risk associated with greater fire tending that has not yet been characterized. When cooking meals on a 3-stone fire that requires long cooking times, such as beans, the cook will often prepare a large fire and perform other household tasks while the beans are cooking. Use of the EcoZoom stove requires a behavior modification to persuade the cook to stay by the fire while the meal is cooking. Additionally burning of wet wood in an improved stove can be more difficult than a 3-stone fire, so a cook often prefers to use the easier cooking method and therefore it is suggested that a careful examination of cooking practices, and focusing on those practices rather than the intrinsic benefits of the technology may result in higher adoption rates[58].

42.4% of observed cooking events occurred outdoors as instructed through education and training activities. While the EcoZoom stove has the potential to reduce indoor air pollution compared to traditional stoves, the primary reduction may likely come from moving cooking out of the home. As less than half (42.4%) of observed cooking events occurred outdoors as instructed through education and training activities, further messaging targeted at cooking location will need to be performed to increase outdoor usage.

A 65.8% reduction in wood usage by users of the EcoZoom stove is likely to significantly reduce time to collect wood and expenditure on fuelwood. Much of the wood use in Rwanda is with small sticks and branches which burn fast on three stone fires. Wood reduction was calculated through the ratio of wood bundles used before and after receiving the EcoZoom stove. In order to better quantify wood savings, additional methods will need to be employed to better understand wood usage such as the kitchen performance test which can evaluate stove performance in real-world settings[59].

With respect to both the filter and stove, behavior in *Ubudehe* categories 1 and 2 was similar to the overall population. This suggests that similar results could be expected during a large distribution of only *Ubudehe* 1 and 2 households. However, the effect of distributing to only a part of a village while the other households do not receive the technologies is unknown.

Free Distribution

Recent studies have examined cost-sharing for bed-nets, cook-stoves and water treatment systems and have found that there is no correlation between free distributions and low adoption rates[34]. Meanwhile, a study examining point-of-use chlorination through marketing campaigns and coupon schemes found these to be ineffective strategies but found free chlorination dispensed at water sources along with community providers as the most effective strategy in potentially preventing diarrheal incidence in areas like rural Kenya[35]. Furthermore, Bensch and Peters determined that a free stove program in Senegal resulted in high uptake of almost 100% of households[36].

These studies suggest that adoption and price are not fundamentally correlated, and that other factors including community engagement, government support and education are worth more careful study. With respect to the private-public partnership described here, the free giveaway nature of the program did not appear to adversely affect technology adoption on a community level, and resulted in a broader population exposure to the interventions than would have been possible via a retail effort over the same time period. The high rate of exclusive use of filters suggest that free distribution did not impact filter use, though it may have impacted intervention stove use.

Public-Private Partnership

The extensive logistical and behavior change messaging components of this program require sustained funding. Rwanda is not yet able to finance all health service activities directly; it relies both on direct donor funding to government programs, as well as careful coordination of programs managed by international non-profits and health sector businesses. By 2002, the government was spending 8.6% of its revenue on health care, which was only a third of the total costs, the remainder covered by donors. Donation based non-profits are not providing services to the target populations serviced by this program. The business model anticipated by the for-profit implementer is designed to recuperate invested costs by the generation and sale of carbon credits associated with the proportion of the intervention that continues to demonstrate successful behavior change. The outcomes observed to-date support the business model in that high adoption rates will correlate to carbon credit generation sufficient to generate sustainable revenue that will allow continued program investment.

Study Limitations

Many of the results described here are from self-reported survey data that may result in over-reporting because of courtesy bias[60]. Over-reporting was measured in this study through the use of remote sensors which revealed over-reporting in frequency of use of both the water filter and cookstove[48]. This contributes to existing evidence of courtesy bias in self-reported outcomes of product distributions. Additionally while the survey directly asked households about their use of other cookstoves, it did not ask about households about supplementing their drinking water from other sources. To fully understand this issue, additional surveying and analysis is necessary. Respondent fatigue may also have been an issue throughout the study as some households were visited several times during a single month. Additionally the short duration of this study (five months) with less rigorous follow up through at least month 16 doesn't allow for complete characterization of the technologies or long-term adoption.

Acknowledgements

The authors thank the important contributions from colleagues and students at the Rwanda Ministry of Health, DelAgua Health, Vestergaard Frandsen, EcoZoom, Portland State University, the University of Colorado at Boulder and the London School of Hygiene and Tropical Medicine.

Table S1. Reasons for stove and filter problems, repairs and replacements.

	N	%
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Difficult to use	31	18.5%
Doesn't warm the house	20	11.9%
Use of a different fuel	13	7.7%
Other (20)	76	45.2%
Reported stove problems	73	
Pot skirt missing screw	22	30.1%
Pot skirt damaged	8	11.0%
Stove too small	6	8.2%
Difficulty in moving pot skirt to another pot	6	8.2%
Ceramic chamber cracked	4	5.5%
Stick support damaged	4	5.5%
Other (12)	23	31.5%
Reported reasons for continued use of old stove	1386	
More than one stove needed	649	46.8%
Don't have dry wood	330	23.8%
Need to warm house	126	9.1%
Pot is too big for stove	73	5.3%
Other (28)	208	15.0%
Reasons for stove repair	67	
Skirt replaced/Skirt damaged	48	71.6%
Skirt replaced/adjustment screws missing	11	16.4%
Stick support replaced/Broken	3	4.5%
Stick support replaced/Missing	1	1.5%
Other	4	6.0%
Reported filter problems	182	
Filter broken or clogged	45	24.7%
Tubes damaged/eaten by rodents	33	18.1%
Tubes are kinked	26	14.3%
Difficulty in backwashing	22	12.1%
Tap is leaking or broken	18	9.9%
Backwash bulb is damaged	17	9.3%
Other (6)	21	11.5%
Reasons for filter repair*	391	
Filter cartridge clogged	124	31.7%
Tubes replaced from rodent damage	119	30.4%
Backwash water not going into container	62	15.9%
Broken tap handle	39	10.0%
Broken tap - leaking	10	2.6%
Backwash leaking	5	1.3%
Backwash bulb replaced	2	0.5%
Other	30	7.7%

*366 total filters repaired - 25 had multiple problems

Study 2: Process Evaluation and Assessment of Use of a Large Scale Water Filter and Cookstove Program in Rwanda

Barstow CK, Nagel C, Clasen T, and Thomas EA. (2015) Process Evaluation and Assessment of Use of a Large Scale Water Filter and Cookstove Program in Rwanda. Submitted for review to Biomedical Central Public

Abstract

Background

In an effort to reduce the disease burden in rural Rwanda, decrease poverty associated with expenditures for fuel, and minimize the environmental impact on forests and greenhouse gases from inefficient combustion of biomass, the Rwanda Ministry of Health (MOH) partnered with DelAgua Health (DelAgua), a private social enterprise, to distribute and promote the use of improved cookstoves and advanced water filters to the poorest quarter of households (*Ubudehe* 1 and 2) nationally, beginning in Western Province under a program branded *Tubeho Neza (*"Live Well"). The project is privately financed and earns revenue from carbon credits under the United Nations Clean Development Mechanism.

Methods

During a three-month period in late 2014, over 470,000 people living in over 101,000 households were provided free water filters and cookstoves. Following the distribution, community health workers visited nearly 98% of households to perform household level education and training activities. Over 87% of households were visited again within six months

with a basic survey conducted. Detailed adoption surveys were conducted among a sample of households, 1,000 in the first round, 187 in the second.

Results

Approximately a year after distribution, reported water filter use was above 90% (+/- 4% CI) and water present in filter was observed in over 76% (+/- 6% CI) of households, while the reported primary stove was nearly 90% (+/- 4.4% CI) and of households cooking at the time of the visit, over 83% (+/- 5.3% CI) were on the improved stove. There was no observed association between household size and stove stacking behavior.

Conclusions

This program suggests that free distribution is not a determinant of low adoption. It is plausible that continued engagement in households, enabled by Ministry of Health support and carbon financed revenue, contributed to high adoption rates. Overall, the program was able to demonstrate a privately financed, public health intervention can achieve high levels of initial adoption and usage of household level water filtration and improved cookstoves at a large scale.

Introduction

Contaminated air and drinking water at the household level are significant contributors to morbidity and mortality among rural populations in low-income countries. Household air pollution (HAP) contributes to acute lower respiratory infection (ALRI), the leading cause of death in children under 5 [1]; among adults, HAP is a risk factor for ischaemic heart disease, stroke, hypertension, chronic obstructive pulmonary disease, lung cancer, trachea, bronchus, cerebrovascular disease and cataracts [61–63]. HAP from indoor cooking with solid fuels (coal, wood, charcoal, dung, and agricultural residues) is responsible for 18% of global burden of disease in 2012; indoor cooking is also linked to a half million deaths annually from outdoor air pollution (5). Inadequate and unsafe drinking water is the leading cause of diarrheal disease, which alone accounts for more than 1.4 million deaths annually. Collectively, pneumonia and diarrhea are responsible for an estimated 6.9 million deaths annually [1].

These environmental hazards are further aggravated among impoverished rural inhabitants of sub-Saharan Africa, the vast majority of which cook with biomass fuels on traditional stoves and rely on unsafe water supplies. In Rwanda, where more than half the population is living below the poverty line and more than a third in extreme poverty, 99.0% of rural householders cook with biomass, mainly on open three-stone fires, and only 2.2% have water on their premises [65]. In Rwanda, leading causes of death in children under five include ALRI (16%) and diarrhea (9%)[66].

Household environmental health interventions like water filters and improved cookstoves, combined with on-going comprehensive household engagement, may help address these health issues [62,67]. However, the up-front cost of household filters and cookstoves, together with the need to establish supply chains for consumables, has limited the extent to which they have been scaled up among vulnerable populations, particularly in rural settings. There have been few large-scale adoption studies to assess the use of household water filters and cookstoves promoted programmatically.

Background

In an effort to reduce the disease burden in rural Rwanda, decrease poverty associated with expenditures for fuel, and minimize the environmental impact from inefficient combustion of biomass, the Rwanda Ministry of Health (MOH) partnered with DelAgua Health (DelAgua), a private social enterprise, to distribute and promote the use of improved cookstoves and advanced water filters to the poorest quarter of households (*Ubudehe* 1 and 2) nationally, beginning in Western Province. The project is privately financed and earns revenue from carbon credits under the United Nations Clean Development Mechanism (CDM), a program authorized by the Kyoto Protocol that provides market-priced credits to the implementer based on a formula that includes population coverage and use [68].

DelAgua and MOH first undertook a pilot intervention (Phase 1) to all 1,943 households in 15 rural villages working with recruited Community Health Workers (CHWs) [69]. The London School of Hygiene and Tropical Medicine then undertook a five-month cluster randomized trial among 566 households in three pilot villages to assess coverage and use, the impact of the water filter on fecal indicator bacteria in household drinking water and the impact of the stove on fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) in reported cooking areas [49]. While reported filter use was high (89.2%), 25% reported drinking from other sources at least once during 5 follow-up visits; filter-mounted sensors also showed self-reports to exaggerate use [48]. Overall, the intervention was associated with a 97.5% reduction in mean faecal indicator bacteria

(Williams means 0.5 vs. 20.2 TTC/100 mL, $p<0.001$). Two-thirds (66.7%) of intervention households identified the intervention stove as their main cooking stove, but only 23.3% of intervention households reported that their main cooking area was outdoors. Overall, the stoves were associated with a 48% reduction of 24-h $PM_{2.5}$ concentrations in the cooking area (0.485 mg/m^3 and 0.267 mg/m^3, $p = 0.005$). The reduction was 37% for those cooking indoors ($p=0.08$) and 73% for those cooking outdoors ($p<0.001$) [49]. Following the pilot RCT, 9 of the non-RCT pilot villages were matched with control villages and followed for an additional 12 months to assess longer-term intervention uptake and to test methods for assessing exposure and health outcomes for a larger scale health impact evaluation. The results of the matched cohort study are still being analyzed.

The Phase 1 effort yielded several lessons integrated into the large-scale Phase 2 program. These included design improvements to both the stoves and filters in collaboration with the manufacturers, improved criteria for CHW selection, interactive materials for household education, and targeted curriculum for exclusive and consistent use of both the stoves and filters.

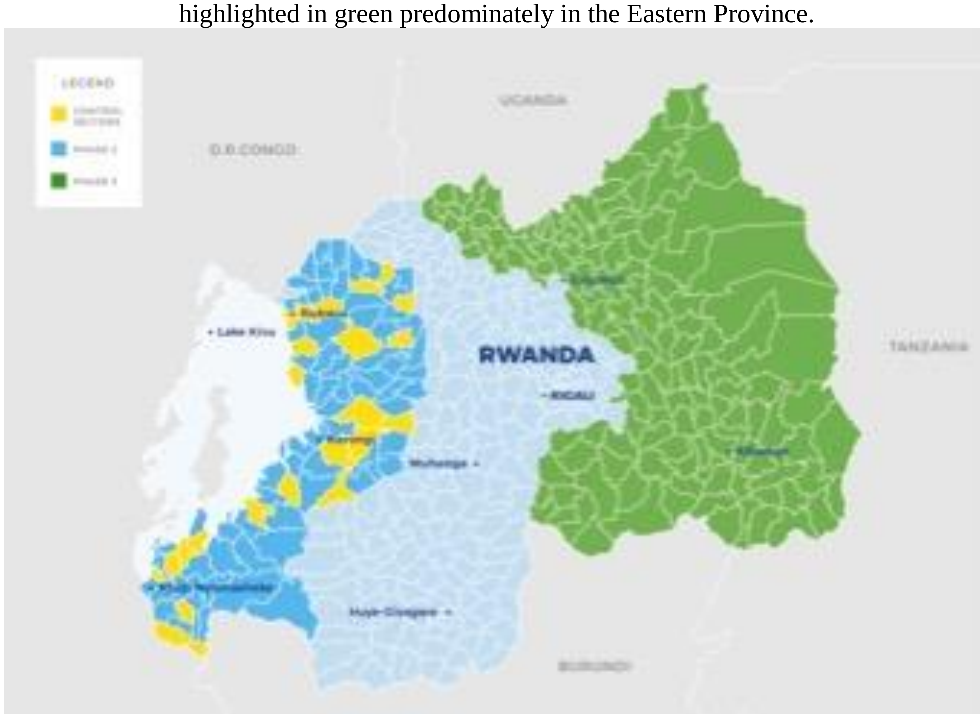
Based on the results from the pilot study, DelAgua and the MOH elected to proceed with the roll out of the intervention throughout the Western Province of Rwanda (Phase 2). For logistical and research purposes, it was agreed that 70 of the 96 sectors (groups of villages that also correspond with catchment areas for primary care clinics) would be covered in the initial round of implementation (September through December 2014); 24 sectors that would be covered later serve as the control group in a sector-level RCT to assess the impact of the intervention on health outcomes (ClinicalTrials.gov, NCT02239250). Two sectors were excluded after a field study determined greater than 50% of *Ubudehe* 1 and 2 households in these areas were primary charcoal users for which the stoves were less suitable.

Methods

Program Description

The program is branded *Tubeho Neza* which means to "Live Well" in Kinyarwanda. *Tubeho Neza* includes the distribution of the Vestergaard Frandsen LifeStraw Family 2.0 household gravity-fed water filter and the EcoZoom Dura high efficiency wood cookstove, and associated community and household education and behavior change messaging. The intervention technologies have been described elsewhere [49]. Recipients of the technologies included all households classified as *Ubudehe* 1 and 2 (the government-recognized poorest 25% of the country) in 70 of 96 sectors in the Western Province (Figure 1). Technologies were also distributed to local leaders including all CHWs, village chiefs and cell level (2 – 16 villages) officials in intervention areas. All households originally enrolled in the Phase I effort were integrated into the *Tubeho Neza* program and received upgraded filters and cookstove servicing. Figure 1 shows expansion plans for Phase 3, in 2016.

Figure 1. Rwanda with Sector administrative boundaries. Phase 2 Tubeho Neza distributions occurred in the dark blue sectors in the Western Province. Yellow regions identify control sectors. Planned Phase 3 activities in 2016 are highlighted in green predominately in the Eastern Province.



Leveraging several behavior change methodologies as described in the pilot study [69], the program provides informational and education contact to the beneficiary at multiple key points to facilitate the adoption and sustained use of the water filter and improved cookstove. Activities include a social marketing campaign before and during distributions, community level product delivery facilitated by local leaders, and household level education performed by CHWs immediately after the household receives the products with ongoing visits at regular intervals.

CHW Selection and Training Program

Rwanda's extensive CHW network includes three CHWs for each village with nearly 11,000 CHWs in the Western Province of Rwanda. CHWs were selected based on criteria including Kinyarwanda literacy, timeliness, responsiveness, smartphone competence, and program knowledge.

CHW trainings were conducted in each of the seven Western Province Districts with an average of ten CHW Sector teams and 124 CHW participants per training. Each training included 2.5 days of lessons with topics related to the use and maintenance of the technologies, smart phone and application based data collection, basics of survey enumeration, and communication and engagement with household members, with emphasis on learner-participatory, interactive techniques. Lessons were designed with as much hands-on and practice based learning as possible, partly to impart knowledge to CHWs in the most effective manner, but also to model the engagement method. Specifically, use of a smart phone was known to be a challenging skill for many CHWs, and thus over 40% of the training revolved around learning smart phone based skills. Additional importance was placed on non-exclusive engagement with both genders and across all age ranges.

Social Marketing

To create awareness around the program and provide initial knowledge for the products, radio advertisements and sensitization meetings were conducted before households received their water filters and improved cookstoves. Advertisements were run on three different regional radio stations with combined reach across the majority of Western Province. Two different radio scripts were aired, one before the start of the campaign and the second during distributions. The first advertisement focused on creating awareness around the *Tubeho Neza* campaign itself and the adverse health and environmental effects of indoor air pollution and contaminated water. The second advertisement then focused on the benefits of the products and the positive effects of product use on a household.

Sensitization meetings were conducted by the South African marketing agency, EXP, anywhere from one day to two weeks before the households in the community were to attend the distribution meeting to collect their products. The focus of these meetings was to introduce the larger community to the program, while providing initial exposure to the water filter and improved cookstove before households received them. Demonstrations of the products' use were conducted emphasizing potential benefits, with the aim of generating excitement and initial user knowledge. Finally, local authorities took the opportunity to communicate the date and location of the upcoming distribution meeting, as well as reach out to the specific targeted households, in order to maximize turnout for the distribution meeting.

Distributions

Prior to distributions, 360 unique distribution points were identified, including government offices, schools, churches and health facilities. In addition, an extensive process of updating the beneficiary list was completed before distributions. The list identifying the *Ubudehe* category for each household was completed in 2012, two years before the program. These lists were distributed to village chiefs who were asked to update them based on the current residents of his/her village. After all storage and distribution points and the schedule were established, the Rwanda National Police were responsible for transporting products from the capital to the 360 established locations.

Each distribution was facilitated by local officials who gave opening remarks regarding the program. CHWs then performed a skit that portrayed a family before and after receiving the water filter and cookstove. The skit ends with the singing and dancing of the *Tubeho Neza* song. After the skit, households were asked to queue in order to receive the products. Discrepancies or disagreements on distribution lists were arbitrated by village chiefs or local CHW leaders. A separate smartphone-based distribution form was collected for each household which included household identification information, photos and signature of recipients, and barcode scanning of the water filter and cookstove. Households were then instructed to bring their products home and wait to be visited by a CHW.

Distributions occurred throughout the Western Province, starting with four distributions in the first week and reaching 59 distributions at the peak of the campaign. On average 31 distributions were conducted per week during the 13 weeks of the campaign. Distributions occurred at the cell level, which on average consists of seven villages. The size of a distribution varied from 25 – 753 households with an average of 256 households per distribution. Given the varying size of a particular cell, distributions took anywhere from several hours to two days.

Initial Household Visit

Following distribution activities, CHWs convened with their DelAgua supervisor to divide up household clusters and visiting routes, devising a strategy for completing all household visits, with input and sometimes accompaniment from authorities most familiar with the particular areas. Rwanda's challenging terrain often meant CHWs had to travel distances of several kilometers to reach beneficiary households. Household visits were performed for a total of 98 days with an average of 1037 household visits performed each day. On average 79 CHWs were performing household visits six days a week. At the peak of the program 309 CHWs performed 2274 household visits in a single day. Visits were tracked through a smart phone based form, which could be tracked cross-referencing several parallel identifiers in the distribution forms to determine any households who received products at distribution but had not yet been visited by a CHW. As with the distribution forms, additional analysis was performed to identify duplicate household visits or other possible data entry errors.

Household visits included two components; a brief baseline survey and an extensive education and training session. The survey included baseline fuel, stove, cooking location, water source, and any water treatment methods currently used by the household. Additionally general household identifying information was collected (names, phone numbers, identification numbers, GPS coordinates) and product barcodes of the newly received filter and cookstove were scanned to track products to specific household locations.

Household education included use of interactive teaching tools, primarily an illustration based flipbook and a poster, customized to the household's size and daily routines, which was hung in each household. The design of the flipbook included colorful graphic images illustrated from photographs (example pages shown in Figure 2). Images were piloted with several families to develop appealing and culturally appropriate images. Each page of the flipbook included a specific message to be communicated to the family by the CHW. Instructional pages included a step-by-step process to perform usage and maintenance tasks, while prompting the CHW to physically perform the tasks and have members of the family demonstrate usage. Households had been advised during the distribution meeting to fill the water filter in preparation for the CHW visit, as the initial filling of the backwashing chamber might in some cases exceed household visit time, so that this maintenance feature could be demonstrated with full functionality. The poster included several activities personalized for each family such as circling the number of times to fill a filter in order to provide the entire recommended water consumption amount to all members of a family per day based on its size.

Figure 2. Example pages from educational flipbook used by CHWs during household education visits.

Key messages included:

- Family Oriented - Both the flipbook and poster emphasized ownership of the products by all members, aspiring to be a healthy and happy *Tubeho Neza* family. CHWs were encouraged to engage all available members of a household in the visit.
- Health, Environment and Livelihood Consequences and Benefits – Common diseases and health effects from contaminated drinking water and indoor air pollution were highlighted, as well as possible environmental effects from deforestation. Many of these

consequences were then discussed in relation to benefits from using the technologies including financial savings, time savings and cleanliness.

- Comprehensive Filter Description – Phase I households expressed interest in understanding exactly how the filter worked as it was seen as intimidating which made some households hesitant to use and adopt the product. A pictorial description of membrane filtration and the cleaning process was added which helped households understand the importance of backwashing.
- Hydration – In response to skepticism from Phase I households over the program's messaging of the importance of consumption of two liters of water per person per day, messaging was developed to promote hydration through explanation of its health benefits, including reinforcement of the biological importance of water for all ages, young and old.
- Exclusive Use of Filtered Water – Targeted messaging was developed to encourage families to bring filtered water with them to school, work or leisure activities. Families were also asked to designate clean containers as *Tubeho Neza* containers to be used only for safe water storage. A hatch mark was drawn on the containers to distinguish these from others, and households were trained to clean such containers once a week.
- Wood Storage – The difficulty in using the EcoZoom stove with wet or damp wood was indicated by many Phase I households. Households were asked to designate a specific area where fuelwood could be stored so that it could be dry for future use.
- Stove Stacking Behavior – To combat stove stacking (use of traditional stove alongside improved stove), examples of reduced cooking times and fuel consumption from using the improved cookstove were emphasized in the flipbook as well as negative messaging around the use of the traditional three stone fires being harmful and wasteful.

- Cooking Location – To provide additional health benefits related to the use of the improved cookstove, households were instructed to cook outside. However, this was difficult for many households with the large amount of precipitation in much of the Western Province. Therefore, messaging highlighted the portability of the stove, to show it could be moved to a doorway or other household location both well-ventilated and covered.

When CHWs finished the education lesson, beneficiaries were asked to countersign an agreement between their household and a local official acknowledging that the products are for the benefit of the family and are not for sale. A record of this agreement was kept by photographing it using the smart phone. Additionally a shortcode for a repair and replacement hotline was displayed on the poster, which families can contact in case of any problems with the products.

Follow up Household Visits

Following the 2014 distribution, a follow up campaign was implemented which consisted of household visits to all households who originally received products. The follow up visits were conducted in the Spring of 2015 between 6 weeks to 6 months after households received products. All CHWs were deployed within a five-week time period. On average CHWs performed 1176 household visits per day with a peak of 3557 households visited by 604 CHWs in a single day.

A follow up household visit included a brief survey to assess several adoption and programmatic metrics, repair and replacement of broken products, cleaning of the filter's bottom safe storage water container and an education and training lesson.

The CHW follow up survey questions were focused on current water treatment and cooking practices, primarily assessing initial adoption and continued use of the filter and cookstove. Questions included asking households to report their current household behaviors but additional observational measures were included such as the presence of water in a filter or visible cooking practices occurring during the visit to provide more objective data points. The survey was of similar length to the initial household survey and could be administered in approximately 10 minutes.

The household education included emphasis of critical messaging as described previously through similar picture based images presented through a new education material, a yearly calendar, with messaging resembling that used in the original flipbook and poster. Prominence on the calendar was accorded to specific messaging components based on relative priorities of re-visiting, taken from an analysis of the previously mentioned assessment surveys conducted in the quality control activities of the initial household visit campaign. Households were encouraged to use the calendar for their daily lives, as well as events related to the technologies, such as weekly or monthly cleaning tasks. Household members present at the time of visit were again asked to demonstrate use of the products, and CHWs ensured they were able to perform all necessary tasks. Additionally, a *Tubeho Neza* designated safe water sticker, with an illustration of the model *Tubeho Neza* family, was added to safe storage devices previously designated with the *Tubeho Neza* hatch symbol. This was intended, not only to reinforce sanitation behaviors associated with the filter, but also to encourage pride in households' self-identification with the *Tubeho Neza* program when using the safe storage devices out in the community. Finally, all households deemed by the CHW to be correctly using and maintaining the technologies were given a plastic *Tubeho Neza* bracelet as a token of further identification with the program.

To track the follow up campaign, supervisors used a comprehensive smart phone reporting system. Any household that could not be found was reported for as missing, moved, or otherwise unavailable, by supervisors while any unaccounted for product was reported as stolen, sold or at another location. Any product that could not be repaired by CHW's at the time of the visit was reported by the CHW as "in need of repair" in a section in the survey. DelAgua supervisors provided CHW teams with certain filter replacement parts, including taps, backwashing tubes, backwashing container, and pre-filters, to be used in CHW-repairs, which were also tracked through the Follow Up Survey. Additionally, in households found to have sold or attempted to sell one or both of the products, or in households found to have been initially distributed, by mistake, product to which they were not entitled, any remaining product was repossessed by a Supervisor, returned to a local storage facility, and reported.

To combat potential algae growth in the bottom container of the filter, as seen in some Phase I households, a mandatory cleaning of each of the filters was performed by CHWs. Households were not instructed to clean the filters themselves, as this may introduce contamination.

On-Going Promotion Activities

Behavior change and reinforcement activities are ongoing throughout the intervention area. DelAgua staff reside full time in each of the seven Districts of Western Province to manage these activities. Ongoing behavior change activities include:

- CHW Cooperative Meetings – Staff provide additional educational messaging, receive updates on adoption within households and facilitate incorporation of the *Tubeho Neza* program into other health programs.
- Community Meetings – Staff carry out informational sessions which address specific educational goals at common community meetings such as the community service day

(*Umuganda*), market days, and other official meetings, as well as to provide repair and replacement services.

- Field and Household Visits – Staff have frequent presence at the household level, through both announced and unannounced household visits to assess technology adoption involving local officials and other local stakeholders.
- Community Hygiene Clubs – Organized activities address community hygiene clubs specifically with benefits and ask members to advocate *Tubeho Neza* products.

DelAgua staff are also responsible for repair and replacement of technologies. Reporting of broken products initiated by households or community leaders calling staff directly or the DelAgua 'shortcode' hotline. Each report is documented and assigned. Staff is then responsible for performing community based repairs or replacements in areas where they are needed, which are reported when completed and tracked in a Work Order system. Replacement parts are stored at the District and Sector level to provide easy access for staff.

Survey Methods

Two types of survey data are described throughout this study; those collected by CHWs on nearly 100% of all households and data from a verification survey administered to a sample of the households. Throughout the results section, these surveys will be referred to as "CHW" or "VS" respectively to distinguish the origin of the data.

All surveys were tracked through electronic forms sent to the DelAgua server, hosted by doForms, Inc. An online dashboard tracked the number of forms received against expected target numbers. Additional analysis was completed on a dashboard to identify duplicate or abnormal forms, which could then be relayed to field staff for arbitration. Data was then analyzed using R-Project, an open source statistical software. Any missing data was excluded from the analysis and any outlier exclusion is noted in the analysis.

CHW Surveys

Data was collected by CHWs during three distinct activities; during the distribution, at the initial household visit approximately a day to a week after distribution, and the follow up visit conducted approximately six weeks to six months after distribution. Metrics addressed in each survey are described throughout the previous section. All CHW surveys were conducted on 100% of households unless households could not be found.

Verification Surveys

Two rounds of detailed verification surveys were conducted; one between January and April of 2015, approximately six weeks to six months after distribution, and the second between July and September of 2015, approximately ten months to a year after distribution. The surveys were designed to provide information to the implementer while at the same time satisfying the verification requirements for carbon credits. The surveys were administered by DelAgua staff and included parameters required by the UN CDM monitoring guidelines and methodologies [70]. The CDM also requires a third party auditor to verify survey data and perform field visits to a sample of surveyed households. Additional guidance included a World Health Organization manual on monitoring and evaluation for household water treatment programs [71]. Additional questions were included to assess environmental, health, social and livelihood benefits of the program. The survey instrument consisted of over 100 questions and took approximately 45 minutes to an hour to administer. It was piloted extensively and enumerators were required to attend a three day training on administration of the survey including field based practice surveys in households.

The sampling strategy differed in each survey round. For the first verification survey, a two-stage, cluster sample design was employed. In the first stage, 320 villages in Western Province were randomly selected with probability proportionate to size (PPS) sampling (the number of recipient households was used as the measure of size). In the second stage, three households within each village were randomly selected using simple random sampling (SRS). This resulted in a self-weighted sample of 960 households. At the end of the sampling period, an additional 40 households were selected using SRS and added to the sample to meet CDM requirements, bringing the total number of surveyed households to 1000. During the second verification, only a simple random sample was used, for 187 valid surveys. Household that could not be found, did not consent or did not have an adult over the age of 18 responding were not surveyed and the next household in the randomly generated list was visited. To avoid a potential source of survey bias, surveyors were not provided with this list in advance, and instead contacted the survey manager for the next house on the list when necessary.

Ethics and Consent

The Rwanda National Ethics Committee (IRB #197/RNEC/2014) approved the protocol including all questions and the consent procedure for all CHW surveys and the verification survey. Each household gave informed, verbal consent after receiving details regarding the purpose of the survey. All respondents had to additionally be over the age of 18. Verbal consent was requested and approved based on the high percentage of illiteracy within the study population. Consent was administered through the smartphone survey with all records stored on a password protected server. Participants were given the opportunity to ask questions before consenting to participate. Additionally all households, regardless of consenting to the surveys were able to retain the filter and cookstove.

Results

Product Delivery

A total of 457,778 people across 101,778 households received water filters and cookstoves during the initial campaign distribution. Of these households, 88% (89,609) were households classified as *Ubudehe* 1 or 2 with the remaining 12% (12,157) consisting of households from local cell and village officials, local community health workers and pilot households outside of the *Ubudehe* 1 and 2 classification (Table 1). Following the distribution, community health workers visited 97.8% (99,515) of households to perform household level education and training activities. Average household size was 4.5 with 0.61 children under five. Before receiving the water filter and cookstove, 89.0% households reported firewood as their primary fuel source with three quarters (76.1%) of households reporting the traditional three stone fire as their primary cookstove and the majority (59.2%) reporting primarily cooking indoors. Most households reported the public tap (43.6%) or protected spring (31.1%) as their primary water source with a quarter (26.6%) reporting treating their water before receiving the filter mostly by boiling (80.7% of households reporting treating their water) (Table 2).

Table 1. Program Delivery

	Product Distribution	Initial Household Education Visit		Follow up Household Visit	
	n	**n**	**% of distribution**	**n**	**% of distribution**
Households Reached	101,778	99,515	97.8%	98,804	97.1%
Ubudehe 1 or 2 Households	89,609	87,728	97.9%	86,859	96.9%
Households Outside of Ubudehe 1 or 2	12,157	11,787	97.0%	11,945	98.3%
Total Beneficiaries	457,778	451,236	98.6%	449,882	98.3%

Table 2. Baseline Metrics

	n	%	95% CI
Household Size	4.5 (SD: 2.1)		
Children Under 5	0.61 (SD: 0.89)		
Baseline Cooking Location			
Indoor	57553	59.2%	0.31%
Outdoor	7910	8.1%	0.17%
Separate Kitchen	31627	32.5%	0.29%
Other	125	0.1%	0.02%
Baseline Primary Stove			
Traditional 3-Stone Fire	75690	76.1%	0.27%
Rondereza	19564	19.7%	0.25%
Imbabura	3176	3.2%	0.11%
Other	1058	1.1%	0.06%
Additional Baseline Stoves			
Traditional 3-Stone Fire	75070	75.3%	0.27%
Rondereza	19053	19.1%	0.24%
Imbabura	3406	3.4%	0.11%
Other	2195	2.2%	0.09%
Baseline Fuel			
Wood	88583	89.0%	0.19%
Straw/Shrubs/Grass	7124	7.2%	0.16%
Agricultural Crop	283	0.3%	0.03%
Charcoal	3159	3.2%	0.11%
LPG/Natural Gas/Biogas	331	0.3%	0.04%
Other	35	0.0%	0.01%
Primary Water Source			
Public Tap	43389	43.6%	0.31%
Protected Spring	30935	31.1%	0.29%
Unprotected Spring	10627	10.7%	0.19%
Handpump	4037	4.1%	0.12%
River	3648	3.7%	0.12%
Protected Dug Well	2359	2.4%	0.09%
Piped in Home or Compound	1367	1.4%	0.07%
Unprotected Dug Well	1341	1.3%	0.07%
Lake	1061	1.1%	0.06%
Other	682	0.7%	0.05%
Baseline Treating Water	26432	26.6%	0.27%
Baseline Water Treatment Method			
Boiling	21329	80.7%	0.48%
Sur Eau	4295	16.2%	0.44%
Other	808	3.1%	0.21%

Overall, 90% of households identified on the *Ubudehe* list received products. Most households not reached on the *Ubudehe* list were attributed to discrepancies such as households listed multiple times or households which had moved out of the intervention area. Over the course of the initial campaign, 212 (0.2%) products were repossessed for reasons including allocation to the incorrect household (119, 0.1%), a household receiving multiple products (59, 0.1%) or a household selling their filter or cookstove (17, 0.02%).

The follow up campaign reached 98,804 (97.1%) of the households that were originally distributed technologies. CHWs recorded just over 1% of stoves missing (1164, 1.2%) and under 1% of filters missing (930, 0.9%) during the follow up household visits. Missing products were primarily attributed to stolen products (335 (0.3%) stoves, 138 (0.1%) filters), sold products (315 (0.3%) stoves, 261 (0.3%) filters), products being kept at a relative or neighbor's house (263 (0.3%) stoves, 208 (0.2%) filters) and products being stored in a locked room where the CHW could not confirm the presence of the products at the time of the visit (210 (0.2%) stoves, 254 (0.3%) filters). Only minor hardware issues with the stoves were reported by CHWs, and these did not require replacement or repair. However, CHWs performed about 1500 repairs to filters (1460, 1.5%) which primarily consisted of unclogging filters through multiple backwashes (590, 0.6%), reassembling leaking filters (567, 0.6%) and replacing defective or missing parts (252, 0.3%) such as plastic tubing, o-rings, taps, backwashing tanks and pre-filters.

Since the follow up campaign, DelAgua staff have continued to perform repair and replacement activities throughout the intervention area. Approximately 12 months following the original distribution, stoves required minimal maintenance. Filters have required more attention with 187 (0.2%) filter replacements primarily from households trying to disassemble the filters with staff finding either the water nozzle (83, 0.1%) or plastic joint connecting the dirty water and safe storage sides of the filter (36, 0.04%) broken. Additionally 931 (0.9%) filter repairs have been performed, mostly attributable to the replacement of the backwashing tube (649, 0.7%) which is more vulnerable to damage because it is the only exposed soft-goods portion of the filter. Other filter repairs included backwashing clogged filters (117, 0.1%) and the reassembling of the joint between the filter (26, 0.03%) when it did not require a full replacement.

Social Marketing Activities

Households participating in the verification survey reported first hearing about the program through local officials (38.9%), the initial distribution meeting (20.8%) or their local CHW (14.9%). The two targeted social marketing activities, sensitization meetings and radio advertisements, were not widely reported as the initial pathway for program awareness with just 9.2% and 1.9% respectively of households reporting as their first exposure to the program. However, over three quarters (75.7%) of households did report attending the sensitization meetings while only a quarter of households (23.2%) reported hearing any of the radio advertisements.

Water Filter Adoption Indicators

Tables 3 and S2 detail water filter adoption indicators, including values described below. The CHW follow up survey of the majority of households and the two more comprehensive verification survey rounds of a subset of the households, all measured the reported filter adoption above 90% and observed filter adoption above 75%. During the CHW follow up visits, 94.1% of households confirmed treating the last water they consumed with 99.5% of those households reporting using the LifeStraw filter as the water treatment method (93.6% filter adoption population-wide). The first verification survey conducted concurrently with the CHW follow up survey, measured 95.9% treating the last water and again 99.5% reporting the filter as the treatment method (95.4% filter adoption including non-treaters). The second verification, performed at least 10 months after distribution showed a small decrease in adoption with 92.0% of households reporting treating the last water they consumed and 99.4% reporting the filter as the treatment method (91.4% filter adoption including non-treaters). Observed filter adoption, measured by water present in the filter at the time of the visit, was observed in 78.7% of households visited by CHWs, 81.1% of households during the first verification round and then a decrease of nearly 5% (76.5%) in the second verification round (Table 3).

Table 3. Water Filter Adoption Indicators

	CHW Follow Up Survey			Verification Round 1 - 6 weeks to 6 months after distribution			Verification Round 2 - 10 months to 1 year after Distribution		
	n	**%**	**95% CI**	**n or value**	**%**	**95% CI**	**n or value**	**%**	**95% CI**
Filter Present	97874	99.1%	0.06%	996	99.6%	0.39%	185	98.9%	1.47%
Reported Treating Last Water Consumed	92940	94.1%	0.15%	959	95.9%	1.23%	172	92.0%	3.89%
Reported Last Water Treatment Method									
LifeStraw Filter	92438	93.6%	0.15%	954	95.4%	1.30%	171	91.4%	4.01%
Boiling	466	0.5%	0.04%	4	0.4%	0.39%	1	0.5%	1.05%
Other	3	0.003 %	0.00%	1	0.1%	0.20%	0	0.0%	0.00%
Water Present in Filter	77790	78.7%	0.26%	811	81.1%	2.43%	143	76.5%	6.08%
Reported Ever Drinking Untreated Water at Home				26	2.7%	1.00%	7	4.0%	2.79%
Reported Ever Drinking Untreated Water Away from Home				300	31.0%	2.87%	36	20.3%	5.77%
Reported Location Drinking Untreated Water Away from Home									
While Traveling				160	34.7%	2.95%	22	41.5%	7.06%
School				134	29.1%	2.81%	16	30.2%	6.58%
Work				130	28.2%	2.79%	13	24.5%	6.17%
Don't Know				20	4.3%	1.26%	1	1.9%	1.95%
Other				17	3.7%	1.17%	1	1.9%	1.95%
Reported Filtered Water Quantity (lppd) - Inclusive of Non-Users				1.64 (SD: 1.21)			1.63 (SD: 1.24)		
Reported Storing Filtered Water				663	68.5%	2.88%	114	64.4%	6.86%
Storage Vessel									0.00%
Covered Container with Lid				551	80.3%	2.46%	108	93.9%	3.43%
Uncovered Container				118	17.2%	2.34%	5	4.3%	2.92%
Other				12	1.7%	0.81%	2	1.7%	1.87%

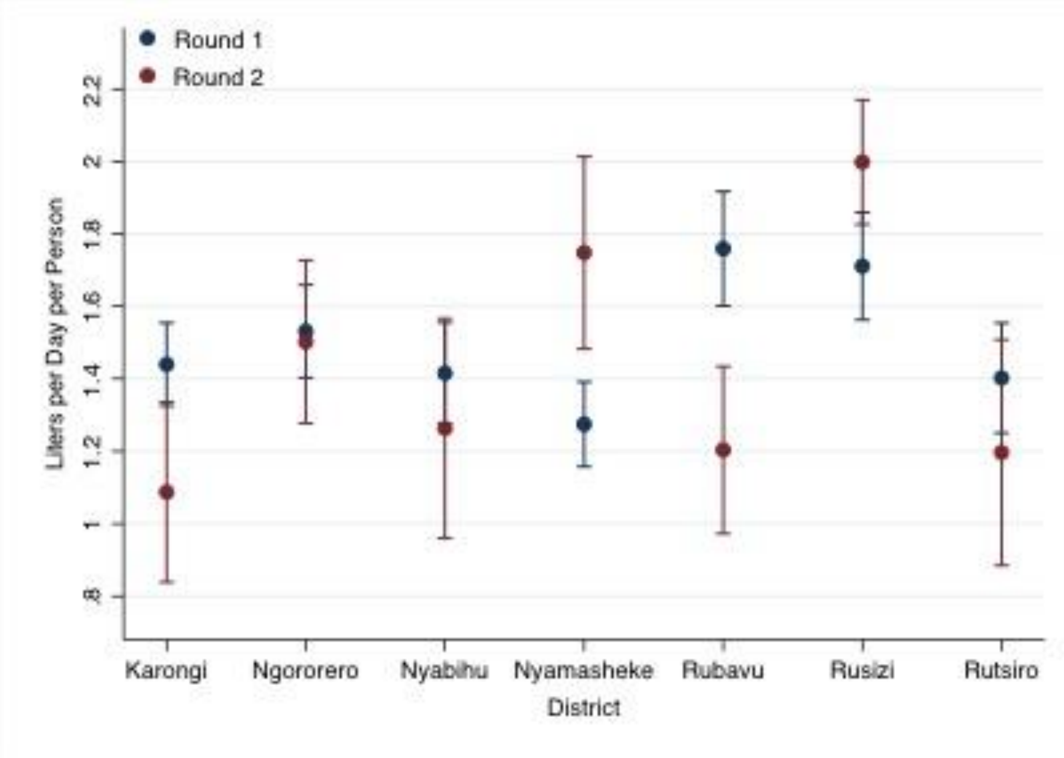
Additional questions were asked of verification survey households only. During both rounds, over 80% of households reported filling the filter today (44.8% - 1st VS, 41.8% - 2nd VS) or yesterday (42.8% -1st VS, 44.6% - 2nd VS) with the remainder (12.4% - 1st VS, 13.6% - 2nd VS) reporting filtering more than two days ago or not knowing the last time the filter was filled. Additionally households were asked to demonstrate use of the filter. Enumerators recorded performance in meeting up to seven actions. Most households in both rounds (97.5% - 1st VS, 97.3% - 2nd VS) were given a rating of sufficient or higher, with nearly 50% (48.9%, 43.8%) receiving excellent ratings. Only 25 households in the 1st round and 5 households in the second round (2.5% - 1st VS, 2.7% - 2nd VS) were given a rating of insufficient and thus unable to demonstrate proper usage of the filter.

Households who did not report treating their water during either verification survey round (56 households total), reported this was due to habit (26.9%), their filter being damaged (16.4%) and no availability of water in the home (13.4%). While the 6 verification households who reported using a different treatment method, did so because their filter wasn't working (36.4%) and they didn't know how to use the filter (27.3%).

Extensive piloting was conducted to determine the likely least subjective method of determining water volume treated. Quantity of water treated was calculated by the size of the vessel reported used to fill the filter multiplied by the reported number of times the filter was filled each day. This was divided by the number of persons (adults and children) living in the household to yield the liters per person per day (LPPD). Average filtered water volume across the sample, including non-users (0 liters per day) was 1.48 (SD= .80) liters per person per day during the first round and 1.44 (SD=.72) liters per person per day during the second round. The majority of households (81.9% - 1st VS, 84.2% - 2nd VS) use filtered water only for consumption with the remaining households (18.1% - 1st VS, 15.8% - 2nd VS) using filtered water for additional purposes including cleaning the filter (40.9% - all VS), washing dishes (29.6% - all VS) and cooking (18.7% - all VS). Households reported a 140% increase in the first round (SD: 139%) and a 161% increase in consumption of water from before receiving the filter to after.

Differences in household water filter use between the seven districts in the Western Province and across verification survey rounds were assessed using linear regression with robust standard errors. We observed significant differences in mean LPPD between districts in both round 1 ($p<.001$) and round 2 ($p<.001$). During round 1, mean LPPD ranged from 1.28 (95% CI=1.16 to 1.39) in Nyamasheke to 1.71 (95% CI=1.56 to 1.86) in Rusizi. During round 2, mean LPPD ranged from 1.09 (95% CI=.84 to 1.34) in Karongi to 1.99 (95% CI=1.83 to 2.17) in Rusizi. While there was no overall difference in LPPD between round 1 and round 2, there were statistically significant increases in the districts of Nyamasheke (Δ=.47, 95% CI=.18 to .76, p=.001) and Rusizi (Δ=.29, 95% CI=.06 to .51, $p = .013$) and decreases in the districts of Karongi (Δ=-.35, 95% CI=-.62 to -.08, p=.012) and Rubavu (Δ=-.56, 95% CI=-.84 to -.28, $p<.001$) (figure 3).

Figure 3. Mean reported filtered water consumed per person per day by district and verification survey round.



Drinking untreated water was reported in 369 of verification survey responses with 33 (2.9%) households reporting drinking some untreated water at home and 336 (29.3%) households reporting drinking some untreated water away from home. When drinking water outside of the home, households were primarily traveling (35.4%), at school (29.2%) or at work (27.8%).

While the filter itself has approximately 5.5 liters of storage capacity, 67.8% of households across both verification rounds report storing additional filtered water. The majority (82.8%) store in a covered container which is usually a jerry can of various sizes. Households who store water report cleaning their storage container at least once a week (96.8%) mostly with filtered water (44.9%) and untreated water (24.2%). Additionally the safe storage symbol which was promoted through the program to be affixed to any storage containers designated for safe water storage was observed on 89.3% of containers identified as water storage containers by households.

The primary maintenance task required for the filter is backwashing of the filter membrane. Most verification households (95.5%) reported backwashing their filter every time they filtered water as advised during household education.

Additional findings include that many (70.9%) households in the verification sample share water with people outside their household. Of the households that shared water, only 19.7% reported usually sharing, while the remaining 80.3% reported sharing sometimes or rarely. Verification households generally did not have negative feedback on how to improve the filter, with most households (69.4%) reporting no changes to the filter. Other responses included increasing the volume (8.9%), adding a stand to the bottom of the filter (5.8%) and providing a cleaning accessory for easier maintenance (4.9%). Additionally households primarily reported that they liked the filter because it provided clean water (43.7%), they like the taste of the water (14.2%), it provides safe water storage (10.6%) and it saves fuelwood from not having to boil water (10.3%).

Improved Cookstove Adoption Indicators

Tables 4 and S3 detail water filter adoption indicators, including values described below. 92.8% of households in both the CHW survey (91,704 of 98,804) and the first verification survey (928 of 1,000) reported the EcoZoom stove as their primary cookstove, with a small decrease to 89.3% during the second verification round. The next most frequent response was the traditional three stone fire with less than 5% for the CHW survey and the first verification round (4.9%) with an increase to 9.6% during the second verification round. When asked which stove was cooked on during the last cooking event, EcoZoom use reduced to around 80% of responses (79.2% CHW, 82.0% 1st VS, 80.5% 2nd VS) while the traditional three stone fire increased by less than 15% for all rounds (14.6%). Observed EcoZoom use was also lower based on stoves that CHWs and enumerators witnessed cooking on at the time of the household visit (75.2% CHW, 77.9% 1st VS, 83.3% 2nd VS). Additionally, households reported use of the pot skirt, in about 7 out of 10 cooking events during both verification rounds (68.9% 1st VS, 67.1% 2nd VS) (Table 4).

Table 4. Improved Cookstove Adoption Indicators

	CHW Follow Up Survey			Verification Round 1 - 6 weeks to 6 months after distribution			Verification Round 2 - 10 months to 1 year after Distribution		
	n	**%**	**95% CI**	**n or value**	**%**	**95% CI**	**n or value**	**%**	**95% CI**
EcoZoom Present	97640	98.8%	0.07%	996	99.6%	0.39%	186	99.5%	1.05%
Stove Type - Cooking at Time of Visit	14358	14.7%	0.22%	181	18.2%	2.39%	30	16.1%	5.27%
EcoZoom	10798	75.2%	0.27%	144	77.8%	2.57%	25	83.3%	5.34%
Traditional 3-Stone Fire	2374	16.5%	0.23%	20	10.8%	1.92%	6	20.0%	5.73%
Rondereza - Locally Made Wood Burning Stove	864	6.0%	0.15%	15	8.1%	1.69%	3	10.0%	4.30%
Imbabura - Locally Made Charcoal Stove	200	1.4%	0.07%	6	3.2%	1.10%	0	0.0%	0.00%
Reported Last Time Cooking Stove									
EcoZoom	80954	79.2%	0.25%	838	82.0%	2.38%	157	80.5%	5.68%
Traditional 3-Stone Fire	14942	14.6%	0.22%	118	11.5%	1.98%	27	13.8%	4.95%
Rondereza - Locally Made Wood Burning Stove	4877	4.8%	0.13%	53	5.2%	1.37%	7	3.6%	2.67%
Imbabura - Locally Made Charcoal Stove	936	0.9%	0.06%	12	1.2%	0.67%	4	2.1%	2.03%
Other	482	0.5%	0.04%	1	0.1%	0.19%	0	0.0%	0.00%
Reported Primary Stove			0.00%						
EcoZoom	91704	92.8%	0.16%	928	92.8%	1.60%	167	89.3%	4.43%
Traditional 3-Stone Fire	4829	4.9%	0.13%	49	4.9%	1.34%	18	9.6%	4.23%
Rondereza - Locally Made Wood Burning Stove	1711	1.7%	0.08%	17	1.7%	0.80%	0	0.0%	0.00%
Imbabura - Locally Made Charcoal Stove	436	0.4%	0.04%	5	0.5%	0.44%	2	1.1%	1.47%
Other	124	0.1%	0.02%	1	0.1%	0.20%	0	0.0%	0.00%
Reported Use of Other Stoves Besides Primary Stove	48013	48.6%	0.31%	475	47.5%	3.10%	96	51.3%	7.16%
Reported Type of Stoves Used Other than Primary Stove									
EcoZoom				63	12.5%	2.05%	20	19.8%	5.71%

Traditional 3-Stone Fire				277	55.2%	3.08%	53	52.5%	7.16%
Rondereza - Locally Made Wood Burning Stove				112	22.3%	2.58%	18	17.8%	5.49%
Imbabura - Locally Made Charcoal Stove				49	9.8%	1.84%	10	9.9%	4.28%
Other				1	0.2%	0.28%	0	0.0%	0.00%
% Of Cooking Events on EcoZoom Stove					86.4% (SD: 18.4%)			92.5% (SD:12.7%)	
Location - Cooking at Time of Visit						0.00%			
Indoor				31	16.8%	2.31%	3	9.7%	4.24%
Outdoor with Cover				14	7.6%	1.64%	0	0.0%	0.00%
Outdoor without Cover				102	55.1%	3.08%	19	61.3%	6.98%
Doorway				17	9.2%	1.79%	2	6.5%	3.52%
Separate Kitchen				21	11.4%	1.97%	7	22.6%	5.99%
Reported Primary Cooking Location									
Indoor	6427	6.5%	0.15%	60	6.0%	1.47%	22	11.8%	4.62%
Outdoor with Cover	4668	4.7%	0.13%	69	6.9%	1.57%	7	3.7%	2.72%
Outdoor without Cover	60548	61.3%	0.30%	695	69.5%	2.85%	134	71.7%	6.46%
Doorway	21259	21.5%	0.26%	115	11.5%	1.98%	11	5.9%	3.37%
Separate Kitchen	5835	5.9%	0.15%	59	5.9%	1.46%	13	7.0%	3.65%
Other	67	0.1%	0.02%	2	0.2%	0.28%	0	0.0%	0.00%
Reported Fewer Cooking Events Per Week Indoors				7.33 (SD: 5.87)			7.23 (SD: 4.61)		
Fuel - Cooking at Time of Visit									
Wood				166	89.2%	1.92%	29	93.5%	3.52%
Straw/Shrubs/Grass				11	5.9%	1.46%	2	6.5%	3.52%
Agricultural Crop				1	0.5%	0.45%	0	0.0%	0.00%
Charcoal				7	3.8%	1.18%	0	0.0%	0.00%
LPG/Natural Gas/Biogas				0	0.0%	0.00%	0	0.0%	0.00%
Electricity				0	0.0%	0.00%	0	0.0%	0.00%
Other				1	0.5%	0.45%	0	0.0%	0.00%
Reported Primary Cooking Fuel									
Wood	95864	97.0%	0.11%	970	97.0%	1.06%	181	96.8%	2.53%
Straw/Shrubs/Grass	2343	2.4%	0.09%	17	1.7%	0.80%	4	2.1%	2.07%
Agricultural Crop	170	0.2%	0.03%	3	0.3%	0.34%	0	0.0%	0.00%
Charcoal	334	0.3%	0.04%	6	0.6%	0.48%	1	0.5%	1.05%
LPG/Natural Gas/Biogas	47	0.0%	0.01%	0	0.0%	0.00%	0	0.0%	0.00%
Electricity	12	0.0%	0.01%	0	0.0%	0.00%	0	0.0%	0.00%
Other	34	0.0%	0.01%	4	0.4%	0.39%	1	0.5%	1.05%

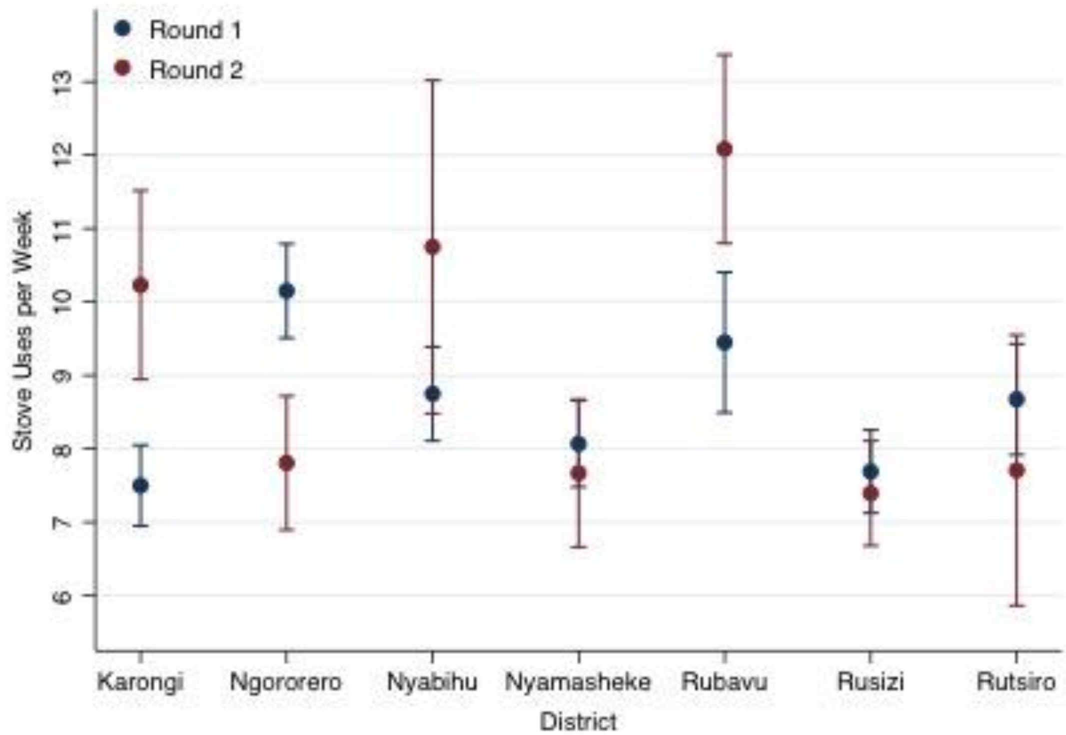
The 10 households (0.8%) between both verification survey rounds which reported not using the EcoZoom stove, reported they didn't know how to use it (23.1%), it didn't warm the house (23.1%) or it was difficult to use (15.4%) as the reported reasons for non-use.

Enumerators performing the verification survey asked households to demonstrate proper cookstove use with each household receiving an internally recorded rating based on number of successful use and maintenance steps completed. Almost all households (98.3%) received a rating of sufficient to use the EcoZoom stove or better with 79.0% of households receiving an excellent rating. Only 1.7% of households received a rating of insufficient for use of the cookstove.

While households reported use of a primary stove, about half the households (48.6% CHW , 47.5% 1st VS, 51.3% 2nd VS) reported usage of other stoves as well. The traditional three stone fire (54.7% all VS) was the most common supplementary stove followed by the *Rondereza* (21.6% all VS). Based on the number of cooking events reported by each verification household, the EcoZoom was used on average in 86.4% (SD: 18.4%) of a household's cooking events during the first verification round and then increased to 92.5% during the 2nd verification round. The most frequently reported reasons for using another stove included difficulty in finding dry fuelwood to use in the EcoZoom stove (32.2%), the need to use multiple stoves at one time (24.2%) and the need to warm the home (15.1%).

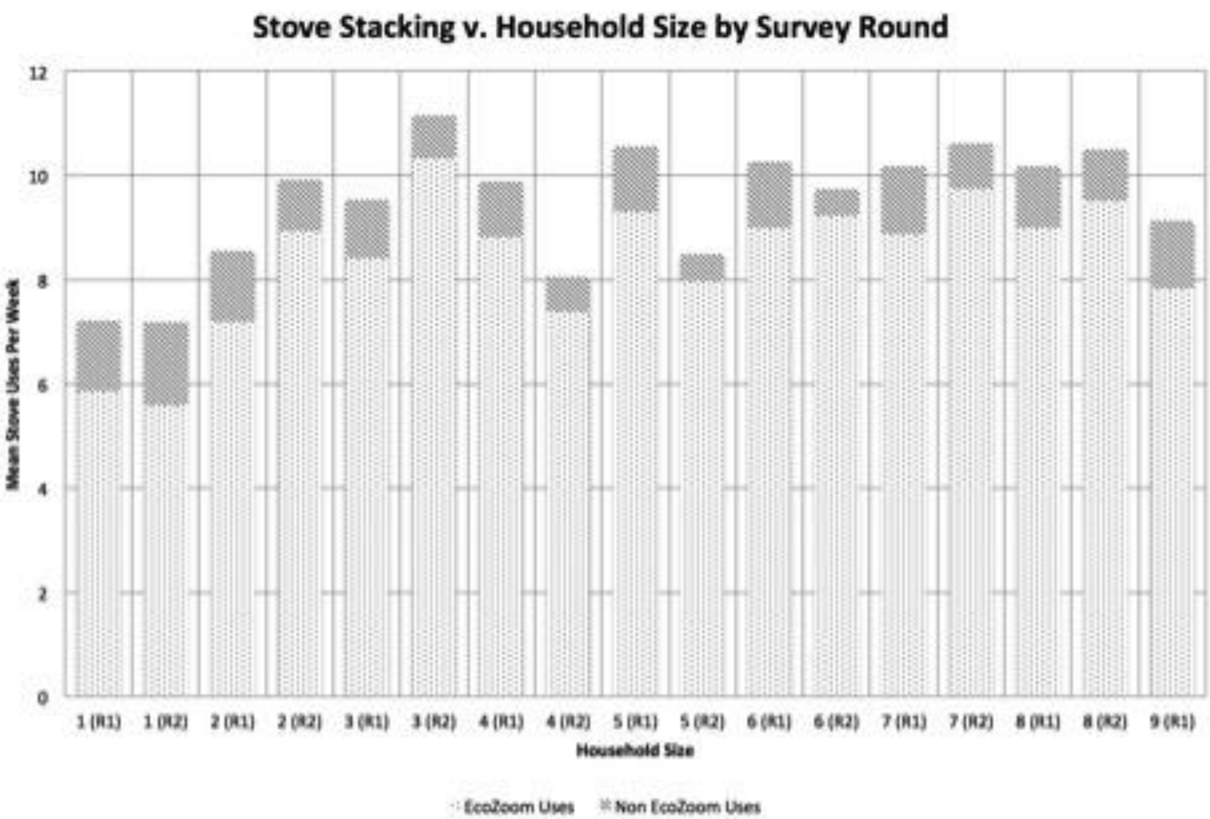
Reported weekly Ecozoom stove use was compared between the seven districts in the Western Province and between survey rounds using Poisson regression with robust standard errors. Significant differences in the count of weekly household Ecozoom uses was observed between districts (p<.001). (Figure 4). The average weekly number of EcoZoom uses reported during round 1 ranged from 7.50 (95% CI=6.95 to 8.05) in Karongi to 10.15 (95% CI=9.51 to 10.79) in Ngororero. During round 2, weekly use ranged from 7.40 (95% CI=6.69-8.10) in Rusizi to 12.09 (95% CI=10.81-13.36) in Rubavu. There was a significant increase in EcoZoom use from round 1 to round 2 in Karongi (Δ=2.73, 95% CI=1.34 to 4.12, p<.001) and Rubavu (Δ=2.64, 95% CI=1.05 to 4.23, p=.001), and a significant decrease in Ngororero (Δ=-2.35, 95% CI=-3.45 to -1.24, p<.001).

Figure 4. Mean reported stove uses per week by district and verification survey round.



To evaluate if stove stacking behavior corresponded to larger household size, the relationship between household size and the weekly count of both baseline (traditional) and EcoZoom stove use was examined using Poisson regression with robust standard errors . We found no significant association between the number of traditional stove uses and household size in either survey round 1 (IRR=1.00, 95% CI=.96 to 1.05, p=.914) or round 2 (IRR=.94, 95% CI=.79 to 1.11, p=.457). The mean number of weekly EcoZoom and traditional stove uses by household size and survey round are shown in Figure 5.

Figure 5. Mean reported improved stove used and traditional stove use per week by household size and verification survey round.



Wood was the primary reported cooking fuel in about 97% of households for all surveys (97.0% CHW survey, 97.0% 1st VS, 96.8% 2nd VS), though only 90.0% of households were using wood in observed cooking events by verification survey enumerators. Most verification households reported only collecting wood (74.1%) while 10.2% reported both collecting and purchasing wood, and the remainder (15.7%) only purchasing wood. 92.8% of households reported storing wood, a highly emphasized part of the education program to promote drying of wet fuelwood, with most households storing wood inside the home (59.7 %) and a third storing in a separate kitchen (34.4%).

The majority of households reported cooking outdoors (66.0% CHW, 76.4% 1^{st} VS, 75.4% 2^{nd} VS) with cooking in a doorway (21.5% CHW survey, 11.5% 1^{st} VS, 5.9% 2^{nd} VS) as the next most frequent cooking location. Slightly lower outdoor cooking (62.7% 1^{st} VS, 61.3% 2^{nd} VS) was observed when households were cooking at the time of the verification household visits with over a quarter (28.1% 1^{st} VS, 32.3% 2^{nd} VS) of households cooking indoors or in a separate kitchen. Households reported cooking indoors fewer times per week than before receiving the EcoZoom stove (7.33 1^{st} VS, 7.23 2^{nd} VS). Primarily households reported cooking indoors because they were getting away from rain (33.8%) followed by cooking on a stove that could not be moved outdoors (18.7%), the need to warm the house (12.3%), security (9.7%) and habit (9.6%).

When asked what could be improved on the stove, the majority of verification household's responses were no improvements (60.4%) with other frequent responses including increasing the size of the stick support (11.9%), increasing the size of the stove top (7.8%) and providing a stove that can use multiple fuels (7.1%). Households additionally reported liking the stove because it cooks fast (32.9%), reduces fuelwood (30.5%) and produces less smoke (19.9%).

Quality Assurance Evaluation

To reinforce the value of household education and interaction, several quality assurance activities were instituted. Before CHWs were allowed to perform household visits alone, a group household visit was conducted with the supervisor to offer feedback and provide clarification for a high quality household visit. CHWs were continually tracked against several metrics including number of surveys per day, average time spent in households and a qualitative evaluation performed by their supervisor. Of 864 CHWs, 774 (89.6%) evaluations were submitted by DelAgua staff. About a tenth (10.9%) of CHWs received an excellent rating, three quarters (74.5%) received a satisfactory rating and the remainder (14.6%) received an unsatisfactory rating. CHW performance during household visits was evaluated by number of surveys, average survey time and an additional qualitative evaluation performed by staff during one of the CHWs first visits. On average CHWs performed seven household surveys per day, spending 31 minutes in a household. CHW evaluations improved slightly from the refresher training with under a tenth (9.1%) of CHWs performing to an unsatisfactory rating, just over 80% (80.9%) receiving a satisfactory rating and 10.0% receiving an excellent rating (Table 5). Some CHWs receiving unsatisfactory ratings were dismissed.

Table 5. CHW Quality Control Indicators

	Refresher Training	**Product Distribution**	**Initial Household Education Visit**	**Follow up Household Visit**
Total CHWs		856	849	820
CHWs per day		71 (31 - 132) SD: 15	208 (139 - 309) SD: 60	444 (41 - 604) SD: 162
Surveys Per Day		1094 (1 -463) SD: 943	1037 (9 - 2274) SD: 659	1176 (3 - 3557) SD: 1237
Surveys Completed per CHW		119 (1 - 714) SD: 61	117 (1 - 259) SD: 41	120 (1 - 226) SD: 39
Surveys Completed per CHW per day		24 (6 -71) SD: 8	7 (2 - 12) SD: 1	5 (2 - 6) SD: 1
CHW Survey Time (minutes)		Not Collected	31 (1 - 119) SD: 14*	46 (1-119) SD: 19*
CHW Evaluations				
Excellent	84 (10.9%)		72 (10.0%)	571 (71.6%)
Satisfactory	577 (74.5%)		585 (80.9%)	224 (28.1%)
Unsatisfactory	113 (14.6%)		66 (9.1%)	3 (0.3%)

*Surveys greater than 2 hours were discounted as outliers

CHW metrics were again tracked during the follow up household visits, including supervisor evaluations of CHW education performance through visiting households previously visited by CHWs. Supervisors evaluated a CHWs completion of all education tasks including the presence of the hung poster, the sticker placed on an appropriate safe storage container, and bracelets given to households for adopting the products. Additionally households were asked several questions related to retention of key messages and asked to demonstrate use. A score was calculated based on these metrics and CHWs were ranked as excellent (71.6%), satisfactory (28.1%) or unsatisfactory (0.3%) performers. High performing CHWs were given a bonus, satisfactory CHWs were given no bonus, and unsatisfactory performers were reviewed further for dismissal from the program. Evaluated households were selected by the supervisors with CHW's having no prior knowledge as to which specific household might be selected. On average CHWs performed five household visits per day, slightly lower than the initial household survey of seven per day due to the longer time spent in households (46 minutes).

Discussion and Conclusions

During a three-month period in late 2014, over 470,000 people living in over 101,000 households were provided free water filters and cookstoves. Approximately a year after distribution, reported water filter use was above 90% (+/- 4% CI) and water present in filter was observed in over 76% (+/- 6% CI) of households, while the reported primary stove was nearly 90% (+/- 4.4% CI) and of households cooking at the time of the visit, over 83% (+/- 5.3% CI) were on the improved stove.

Program Implementation

The extensive process of updating the *Ubudehe* distribution list before distribution proved essential with over 90% of households accurately distributed products. Reaching each individual household for education and training proved to be challenging. CHWs often had to travel many hours to reach target households and thus a large proportion of time and resources was spent on finding the last few households in each village. Local officials and CHWs were helpful in identifying and finding missing households and only about 2% were unaccounted for during the first household visits and 3% during the following up campaign months after the distribution.

Only 21 (0.02%) products were repossessed during the initial campaign due to a product being sold or stolen and 650 (0.65%) products during the months of the follow up campaign (Table S1). Possibly contributing to these low rates are the products marked as “not for sale” and a signed agreement between the household and a local official which outlined the use and benefits of the technologies for only the household who received the technologies. The considerable support of Rwandan government officials in stressing to households the importance of the technologies as well as the already established programs which offer free services to *Ubudehe* 1 and 2 households could be additional contributors.

Social marketing is often promoted as an important strategy in behavior change programs [72]. The *Tubeho Neza* program employed radio advertisements and sensitization meetings as social marketing mechanisms to raise program awareness and provide initial knowledge to households. The use of mass media such as radio advertisements has been used in several water and sanitation interventions [72], however the verification survey only measured a quarter of households ever hearing the radio advertisements and less than 2% identified it as their initial exposure to the program. Similarly only a fraction of households identified the sensitization meeting as their first communication about the program, but many households did report attending the sensitization meeting. Additionally many program staff reported the importance of the sensitization meetings because of the initial exposure of households to the technologies before receiving them. Households were perceived to be more comfortable with initial usage of the products during distribution because of the knowledge gained from the sensitization meetings. Still, the most frequent response to initially hearing about the *Tubeho Neza* program was through local officials, suggesting dissemination of information can effectively be done through already established government programs in Rwanda.

CHWs were an integral part of reaching beneficiaries at the household level and providing quality education and training. Past CHW based programs have shown varied results to the effectiveness of CHWs with evidence suggesting poor performance for a variety of reasons from poor selection of CHWs to low levels of training to lack of on-going support and supervision [73]. The *Tubeho Neza* program sought to mitigate many of these downfalls through an extensive selection and training program paired with an interactive household education platform that was closely evaluated and monitored by program staff. Performance metrics from number of surveys completed to survey time to qualitative evaluations revealed that most CHWs were performing to at least a satisfactory if not excellent level and CHW metrics improved from the initial campaign to the follow up visits. Still, CHW performance was varied as revealed by evaluations from the program staff. One common issue that arose late in the campaign was the time between the initial trainings and CHW teams which started later in the campaign. Some teams did not begin program activities until a couple of months after the District level trainings and low retention of some concepts was noticed. Further training and continued tracking of CHW performance are essential in providing each household with a quality experience.

Technology Adoption and Use

We found high levels of initial adoption of the water filter and cookstove through the first year following distribution of the products. Similar rates of reported adoption of both the water filter and cookstove (around 90%) were seen in the Phase I effort implemented two years prior to the large-scale program (10).

Filtered water quantity increased from the pilot study of 1.27 liters per person per day to 1.63 liters per person per day. The increase may be attributable to increased emphasis in the behavior change program including added messaging about the importance of hydration and specific activities on the household poster which outline how much water should be treated each day in order for the whole family to drink two liters per person day. The high volume of water treated in Rusizi district specifically may be due to increased exposure from recently implemented hygiene and sanitation clubs in only Rusizi district, but further differences between districts are not characterized. However, these differences may be used to customized district level education activities.

Another significant change in the behavior change program was the addition of safe storage messaging. Anecdotal evidence during Phase I suggested that households desired additional storage inside the home and especially while away from the home. In the *Tubeho Neza* program, the majority of households reported storing filtered water with over 80% storing in a container with a lid, thus emphasizing the importance of the added messaging. Still, about a third of surveyed households reported drinking untreated water while away from the home, mostly while traveling. Given evidence that drinking untreated water, even occasionally, can reduce health benefits of water quality interventions [25], continued emphasis on the importance of safe storage and exclusive consumption of filtered drinking water should be promoted within the program.

While current repairs and replacements of water filters have been less than 2% of the total households, long term adoption will likely only be realized if filters are continually maintained in a timely manner with an efficient supply chain. Currently repairs are mostly performed by program staff but in order to create a sustainable maintenance structure, local repairs will be needed. The program is currently training CHWs to perform more repairs and solve maintenance issues before program staff has to travel to individual households or villages to fix issues. Additionally, one of the more frequent repairs is simply from filters being clogged, likely from these households not backwashing the filter enough. More stress will need to be placed on this maintenance task in future trainings to prevent further clogging issues.

While overall reported stove adoption was comparable to the pilot, improvements were made in stove stacking behavior. Reported use of other stoves reduced by over 20% to about half of households reporting still using other stoves, with percentage of cooking events on the EcoZoom stove in the household increasing by at least 15%. While these results are promising in moving towards exclusive adoption of improved stoves, they will not be sufficient in meeting the World Health Organization's guidelines for indoor air pollution [74] which would involve switching to much cleaner fuels and stoves in order to meet recommendations. However, recent evidence suggests that stove interventions may be evaluated based on both the fuel/stove combination and program usage rates, as health gains can be made with lower performing stoves when usage rates are high [75].

One suggested solution to address stove stacking is to provide larger households a second improved stove as many households report desiring a second improved cookstove. However, there was no apparent correlation between household size and stove stacking behavior.

Interestingly number of stove cooking events was highest in Rubavu district, the most urban district in Western Province with the highest rate of charcoal usage. Speculatively, it's plausible this use is associated with reduced cost of purchasing charcoal fuel.

Another frequently reported behavior change barrier during the pilot was the inability to cook on the EcoZoom stove when fuel was wet. Wood storage messaging to promote drying of wood before households needed fuel for cooking was added and promoted highly through the education and training materials, resulting in the majority households reporting storing wood and over 65% having dry wood present in their household at the time of the visit. However the primary reported reason for not only using the EcoZoom stove was still a household's inability to find dry fuel for the EcoZoom.

Rates of outdoor cooking additionally improved from the pilot with 20% higher frequency of outdoor cooking observed during household visits. A common issue during the pilot was the inability to cook outdoors while it was raining and thus cooking in the doorway as an alternative cooking location was highly emphasized during household visits, where many households reported the doorway as their primary cooking location. The behavior change of cooking outdoors may provide additional important health benefits. The potential for reductions in exposure from cooking outdoors were highlighted in the Phase I RCT study where mean $PM_{2.5}$ concentrations were reduced by 39% for those cooking indoors on the EcoZoom with further reductions of 73% when cooking outdoors on the EcoZoom (11).

Free distribution of health products is often debated, centered around claims that free products do not result in adoption rates needed to realize health benefits. This phase 2 program suggests that free distribution is not a determinant of low adoption, consistent with the program design assumptions trialed in the phase 1 program (10). It is plausible that continued engagement in households, enabled by Ministry of Health support and carbon financed revenue, contributed to high adoption rates. Overall, the *Tubeho Neza* program was able to demonstrate a privately financed, public health intervention can achieve high levels of initial adoption and usage of household level water filtration and improved cookstoves at a large scale.

Abbreviations

MOH – Rwanda Ministry of Health
CHW(s) – Community Health Worker(s)
CDM – Clean Development Mechanism
PM – Particulate Matter
CO – Carbon Monoxide
RCT – Randomized Controlled Trial
VS – Verification Survey
SRS – Simple Random Sampling
RNEC – Rwanda National Ethics Committee
LPPD – Liters Per Person Per Day
CI – Confidence Interval

Authors' Contributions

ET and CB were responsible for designing and implementing the program described and drafted the manuscript. ET, CB and CN conducted the data analysis. CB and TC participated in the design of the survey tools and contributed to the drafting of the manuscript. All authors read and approved the final manuscript.

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Competing Interests

Authors Barstow and Thomas are compensated consultants to the funder, DelAgua Health. Their responsibilities include designing and delivering the intervention described. Authors Nagel and Clasen are compensated researchers. Their responsibilities include the health impact study referenced.

Table S1. Product Tracking Indicators

	During Distribution		CHW Follow Up Campaign		DelAgua Staff Repairs (up to 9 Months Post Distribution)	
	n	**%**	**n**	**%**	**n**	**%**
Product Repossessions	212	0.2%				
Distributed to Wrong Household	119	0.1%				
Received Multiple Technologies	59	0.1%				
Sold	17	0.02%				
Stolen	4	0.004%				
Other	13	0.01%				
EcoZoom Stove						
Missing Stoves			1164	1.2%		
Location of Missing Stove						
Stolen			335	0.3%		
Sold			315	0.3%		
Relative or Neighbors Home			263	0.3%		
Locked Room			210	0.2%		
Other			41	0.04%		
Stoves Replaced					2	0.002%
Ceramic Cracked					2	0.002%
Repairs Made to Stoves					7	0.01%
Stick Support Replaced					3	0.003%
Potskirt Screw Missing					1	0.001%
Screws Loose Attaching Stove Together					3	0.003%
LifeStraw Filter 2.0						
Missing Filters			930	0.9%		
Location of Missing Filters						
Stolen			138	0.1%		
Sold			261	0.3%		
Relative or Neighbors Home			208	0.2%		
Locked Room			254	0.3%		
Other			56	0.1%		
Filters Replaced					187	0.2%
Broken Water Nozzle					83	0.1%
Broken Joint Between Tanks					36	0.04%
Water Not Passing Through Filter					24	0.02%
Safe Water Tank Cracked					23	0.02%
Defective/Missing Parts					12	0.01%
Leaking					11	0.01%
Backwashing Lever Broken					6	0.01%
Other					10	0.01%

Repairs Made to Filters		1460	1.5%	931	0.9%
Defective/Missing Parts		252	0.3%	678	0.7%
Backwashing Tube Replaced		0	0.0%	649	0.7%
Tap		55	0.1%	5	0.01%
Backwashing Tank		60	0.1%	6	0.01%
O-ring		99	0.1%	10	0.01%
Prefilter - Wash and Unclog		38	0.04%	1	0.001%
Other		0	0.0%	7	0.01%
Backwash Multiple Times to Unclog Filter		590	0.6%	117	0.1%
Reassemble Leaking Filter		567	0.6%	67	0.1%
Joint Between Tanks Reattached		0	0.0%	26	0.03%
Other		11	0.0%	43	0.04%

Table S2. Detailed Water Filter Indicators

	Verification Round 1 - 6 weeks to 6 months after distribution			Verification Round 2 - 10 months to 1 year after Distribution		
Use and Adoption Metrics						
	n or value	**%**	**95% CI**	**n or value**	**%**	**95% CI**
Reported Last Time Filter was Filled						
Today	434	44.8%	3.08%	74	41.8%	7.07%
Yesterday	414	42.8%	3.07%	79	44.6%	7.12%
Two Days Ago	74	7.6%	1.65%	11	6.2%	3.46%
More than Two Days Ago	40	4.1%	1.23%	13	7.3%	3.74%
Don't Know	6	0.6%	0.49%	0	0.0%	0.00%
Household Demonstration of Use						
Excellent	487	48.9%	3.10%	81	43.8%	7.11%
Proficient	0	0.0%	0.00%	0	0.0%	0.00%
Sufficient	484	48.6%	3.10%	99	53.5%	7.15%
Insufficient	25	2.5%	0.97%	5	2.7%	2.32%
Exclusive Use						
Reported Reason for Not Drinking Treated Water						
Habit	12	31.6%	2.88%	6	33.3%	6.76%
Damaged Filter	8	21.1%	2.53%	3	16.7%	5.34%
No Filtered Water Available at Home	7	18.4%	2.40%	2	11.1%	4.50%
Working Away from Home	5	13.2%	2.10%	3	16.7%	5.34%
Don't Know How to Use the Filter	3	7.9%	1.67%	0	0.0%	0.00%
Other	3	7.9%	1.67%	4	22.2%	5.96%
Reported Reason for Not Using LifeStraw						
Filter Doesn't Work	4	33.3%	2.92%	0	0.0%	0.00%
Don't Know How to Use the Filter	3	25.0%	2.68%	0	0.0%	0.00%
Other	3	25.0%	2.68%	1	100.0%	0.00%
Water Use by Members Outside Household						
Reported Giving Filtered Water to People Outside Household	699	72.2%	2.78%	113	63.8%	6.89%
Reported Frequency of Giving Filtered Water to People Outside Household						
Usually	141	20.2%	2.49%	19	16.8%	5.36%
Sometimes	461	66.0%	2.94%	54	47.8%	7.16%
Rarely	97	13.9%	2.14%	40	35.4%	6.85%
Maintenance						
Reported Backwashing Frequency						
Everytime Water is Filtered	924	95.5%	1.29%	169	95.5%	2.98%
Daily	19	2.0%		3	1.7%	1.85%
Less than Once per Day	20	2.1%		4	2.3%	2.13%
Never	5	0.5%		1	0.6%	1.07%
Water Quantity						
Reported Using Filter for Other Purposes	175	18.1%	2.39%	28	15.8%	5.23%
Cleaning the Filter	68	38.9%	3.02%	15	53.6%	7.15%

Washing Dishes	54	30.9%	2.86%	6	21.4%	5.88%
Cooking	35	20.0%	2.48%	3	10.7%	4.43%
Other	18	10.3%	1.88%	4	14.3%	5.02%
Reported Water Quantity for Purposes Other than Consumption (lppd)	0.479 (SD: 0.389)			0.75 (SD: 1.32)		
Total Mean Water Quantity for Purposes Other than Consumption (lppd)	0.046 (SD: 0.181)			0.052 (SD: 0.386)		
Reported Increase in Consumption of Drinking Water		140% (SD: 39%)			161% (SD: 11%)	
Safe Storage						
Reported Storage Container Cleaning Frequency						
More than Once a Week	479	72.2%	2.78%	51	44.7%	7.13%
Once a Week	164	24.7%	2.67%	58	50.9%	7.17%
Less than Once a Week	18	2.7%	1.01%	5	4.4%	2.94%
Don't Clean the Safe Storage Container	2	0.3%	0.34%	0	0.0%	0.00%
Reported Method to Clean Safe Storage Container						
With Filtered Water	409	43.3%	3.07%	80	55.6%	7.12%
Untreated Water	231	24.4%	2.66%	32	22.2%	5.96%
Soap	166	17.6%	2.36%	16	11.1%	4.50%
Scrubber/Brush	45	4.8%	1.32%	7	4.9%	3.08%
Boiled Water	59	6.2%	1.50%	8	5.6%	3.28%
Other	35	3.7%	1.17%	1	0.7%	1.19%
Storage Container have Safe Storage Symbol Present	604	91.1%	1.76%	90	78.9%	5.84%
User Feedback						
Filter Improvements						
Nothing	812	73.0%	2.75%	140	54.1%	7.14%
Increase the Volume	84	7.5%	1.64%	39	15.1%	5.13%
Add a Stand on the Bottom of the Filter	66	5.9%	1.46%	13	5.0%	3.13%
Provide Cleaning Accessory	49	4.4%	1.27%	18	6.9%	3.64%
Faster Flow Rate	27	2.4%	0.95%	19	7.3%	3.74%
Improve Backwashing Container	23	2.1%	0.88%	9	3.5%	2.62%
Other	52	4.7%	1.31%	21	8.1%	3.91%
Like About Filter						
Provides Clean Water	925	44.5%	3.08%	175	39.9%	7.02%
Like the Taste of Filtered Water	304	14.6%	2.19%	53	12.1%	4.67%
Provides Safe Water Storage	212	10.2%	1.88%	55	12.5%	4.74%
Saves Wood from Not Boiling	211	10.2%	1.87%	47	10.7%	4.43%
Filters Water Quickly	111	5.3%	1.39%	27	6.2%	3.44%
Looks Nice	87	4.2%	1.24%	33	7.5%	3.78%
Easy to Use	84	4.0%	1.22%	15	3.4%	2.60%
Filters All Types of Water	69	3.3%	1.11%	29	6.6%	3.56%
Improves Health	36	1.7%	0.81%	0	0.0%	0.00%
Other	39	1.9%	0.84%	5	1.1%	1.52%

Table S3. Detailed Improved Cookstove Indicators

	Verification Round 1 - 6 weeks to 6 months after distribution			Verification Round 2 - 10 months to 1 year after Distribution		
	n or value	**%**	**95% CI**	**n or value**	**%**	**95% CI**
Use and Adoption Metrics						
Household Demonstration of Use						
Excellent	793	79.3%	2.51%	145	77.5%	5.98%
Proficient	160	16.0%	2.27%	37	19.8%	5.71%
Sufficient	29	2.9%	1.04%	3	1.6%	1.80%
Insufficient for Use	18	1.8%	0.82%	2	1.1%	1.47%
Reported Use of Pot Skirt Per Week	8.24 (SD: 4.52)			7.94 (SD: 4.04)		
Reported % Usage of EcoZoom with Pot Skirt		68.9%	2.87%		67.1%	6.73%
Reported Reason for Not Using EcoZoom						
Don't Know How to Use	3	25.0%	2.68%	0	0.0%	0.00%
Doesn't Warm the House	3	25.0%	2.68%	0	0.0%	0.00%
Difficult to use	2	16.7%	2.31%	0	0.0%	0.00%
Too Small	1	8.3%	1.71%	0	0.0%	0.00%
Don't Like Cooking	1	8.3%	1.71%	0	0.0%	0.00%
Worried About Security of Stove	1	8.3%	1.71%	0	0.0%	0.00%
Keep it Stored Elsewhere	1	8.3%	1.71%	0	0.0%	0.00%
Don't Use Wood for Cooking	0	0.0%	0.00%	1	100.0%	0.00%
Stove Stacking						
Reported Reason for Not Only Using EcoZoom						
Hard to Find Dry Fuel for EcoZoom	194	31.2%	2.87%	54	36.2%	6.89%
Need Multiple Stoves	156	25.1%	2.69%	30	20.1%	5.75%
To Warm the House	92	14.8%	2.20%	24	16.1%	5.27%
Some Food is Difficult to Cook on EcoZoom	33	5.3%	1.39%	1	0.7%	1.17%
Prefer to Use Charcoal	23	3.7%	1.17%	8	5.4%	3.23%
Need Light Source	22	3.5%	1.15%	1	0.7%	1.17%
Pot is Too Big for EcoZoom	22	3.5%	1.15%	7	4.7%	3.03%
Less Time Tending Other Stove	18	2.9%	1.04%	12	8.1%	3.90%
Don’t Know How to Use EcoZoom	12	1.9%	0.85%	2	1.3%	1.65%
Children Can't Cook on EcoZoom	12	1.9%	0.85%	3	2.0%	2.01%
Fuelwood is Too Big to Fit in EcoZoom	8	1.3%	0.70%	0	0.0%	0.00%
Other	29	4.7%	1.31%	7	4.7%	3.03%
Wood Use Reduction						
Reported % Reduction in Wood Bundles		57.0% (SD: 21.4%)			55.1% (SD: 25.2%)	
Cooking Location						
Reported Reason for Cooking Indoors						
Getting Away from the Rain	201	34.5%	2.95%	43	30.7%	6.61%

Using Stove Which Can't Be Moved Outdoors	120	20.6%	2.51%	15	10.7%	4.43%
Warming the Home	71	12.2%	2.03%	18	12.9%	4.80%
Security	54	9.3%	1.80%	16	11.4%	4.56%
Habit	51	8.8%	1.75%	18	12.9%	4.80%
Privacy	24	4.1%	1.23%	14	10.0%	4.30%
For Light	23	4.0%	1.21%	5	3.6%	2.66%
Other	38	6.5%	1.53%	11	7.9%	3.86%
Cooking Fuel						
Reported Method to Obtain Fuelwood						
Collect Wood	740	74.1%	2.71%	136	73.9%	6.29%
Purchase Wood	158	15.8%	2.26%	27	14.7%	5.07%
Collect and Purchase Wood	100	10.0%	1.86%	21	11.4%	4.56%
Reported Storing Wood	930	93.0%	1.58%	172	92.0%	3.89%
Wood Storage Location						
Indoor	565	60.8%	3.03%	93	54.1%	7.14%
Separate Kitchen	309	33.2%	2.92%	70	40.7%	7.04%
Under House Awning	31	3.3%	1.11%	7	4.1%	2.83%
Wood Storage House	20	2.2%	0.90%	1	0.6%	1.09%
Other	5	0.5%	0.45%	1	0.6%	1.09%
Dry Wood Present	659	65.9%	2.94%	150	80.2%	5.71%
User Feedback						
Stove Improvements						
Nothing	743	66.8%	2.92%	112	42.4%	7.08%
Increase Stick Support Size	131	11.8%	2.00%	37	14.0%	4.98%
Larger Stove Top	70	6.3%	1.51%	40	15.2%	5.14%
Stove Which Uses Multiple Fuels	68	6.1%	1.49%	33	12.5%	4.74%
Can be Used Indoors	39	3.5%	1.14%	25	9.5%	4.20%
Provide Additional Pot Skirt	23	2.1%	0.88%	5	1.9%	1.95%
Improvements to Pot Skirt	27	2.4%	0.95%	2	0.8%	1.24%
Add Standing Support	11	1.0%	0.61%	0	0.0%	0.00%
Other	39	3.5%	1.14%	10	3.8%	2.74%
Like About Stove						
Cooks Fast	892	32.9%	2.91%	163	32.7%	6.72%
Reduces Wood	826	30.5%	2.85%	154	30.9%	6.62%
Produces Less Smoke	536	19.8%	2.47%	101	20.2%	5.76%
Don't Need to Blow on Fire	147	5.4%	1.40%	26	5.2%	3.19%
Promotes Cleanliness	96	3.5%	1.15%	23	4.6%	3.01%
Can be Used by All Members of the Family	69	2.5%	0.98%	16	3.2%	2.52%
Portable	60	2.2%	0.91%	8	1.6%	1.80%
Can Use Multiple Sized Pots	36	1.3%	0.71%	5	1.0%	1.43%
Other	47	1.7%	0.81%	3	0.6%	1.11%

Study 3: A Cost-Benefit Analysis of Livelihood of a Large Scale Water Filter and Improved Cookstove Distribution in Rwanda

Barstow CK, Thomas EA, Linden, KG and Bluffstone R. (2016) A Cost-Benefit Analysis of a Large Scale Water Filter and Improved Cookstove Distribution in Rwanda.

Abstract

Public health interventions which target improvements in contaminated drinking water and indoor air pollution may help to reduce two of the leading causes of death in children under 5 in Rwanda, diarrhea and pneumonia. Beyond health impacts, these interventions have the potential to provide economic benefits such as reduction in expenditures on fuelwood and time spent on fuelwood collection, and environmental benefits through reductions in deforestation and greenhouse gas emissions. The purpose of this study was to evaluate one such large scale intervention, the *Tubeho Neza* program in Western Rwanda, in the context of the economic and environmental benefits. A cost-benefit analysis was conducted which monetized program benefits related to fuelwood savings, time savings and environmental benefits whereby these benefits were compared to the overall program cost, over a projected ten year period. Under the expected case, a cost benefit ratio of 7.8 was estimated with the primary contribution from large savings in fuelwood from the improved cookstoves. This study estimates 120,000 tonnes of annual woodfuel savings in the Western Province may currently be attributable to the program, decreasing to 102,000 tonnes in 2024. These estimates suggest that this program alone can more than compensate for the government projected Western Province region woodfuel deficit of 106,000 tonnes per year by 2020. Overall, from a cost-benefit perspective this study suggests that the *Tubeho Neza* program provides sufficient benefits to outweigh program costs.

Introduction

Public health interventions designed to address contaminated drinking water and indoor air pollution hazards in developing countries may under some circumstances deliver benefits beyond positive health impact. Importantly are the economic and environmental benefits which can contribute to the overall suitability and sustainability of an intervention. Advocacy of household water treatment methods replacing boiling can both reduce fuelwood consumption and provide time savings[11,12]. Similarly, implementation of improved cooking stoves has the potential to reduce expenditures on purchasing fuelwood, and time from the collection of fuelwood. Additionally, reduction in fuelwood consumption can result in significant environmental benefits both locally through reduced deforestation and globally through reduced greenhouse gas emissions[13–16].

In the Republic of Rwanda, where two of the largest contributors of mortality among children under five are pneumonia (18%) and diarrhea (8%)[76], the health benefits of interventions which can improve access to clean drinking water and reduce exposure to harmful indoor air pollution have the potential to provide significant health impact. Additionally, Rwanda's 10.5 million people may benefit from the livelihood and environmental benefits from these programs. With over 80% of Rwandans relying on firewood as their primary fuel and over 40% boiling their water for treatment prior to drinking[65], decreased firewood demand from water filters and high efficiency cookstoves could help reduce the shortage in availability of firewood. Additional cost and time savings from reduced fuelwood consumption could help curb some of the economic burden of approximately 80% of Rwandans which live on less than $2 per day[20].

A cost-benefit analysis can provide insight into the relative contribution of these livelihood and environmental benefits, and further contextualize a particular health intervention beyond the potential health benefits. Because public health programs advocating water treatment methods and improved cookstoves can vary greatly in quality, scale and impact, from small community driven projects to large scale government programs, from non-profit to for-profit models, and from subsidized to market based funding mechanisms. Because of the high degree of variability of impacts between these program models, understanding a particular program's ability to deliver benefits to the target population in a cost effective and sustainable way is essential to inform future interventions.

This paper analyzes one such program, the DelAgua Health and Ministry of Health *Tubeho Neza* program in rural Rwanda, through the comparison of the program costs, and the potential benefits of the program related to fuelwood savings, time savings and environmental impact.

Program Setting and Population

The *Tubeho Neza* ("Live Well") program, is a partnership between the Rwanda Ministry of Health (MOH) and the social enterprise, DelAgua Health (DelAgua), to deliver environmental health technologies to the poorest quarter of Rwanda's households. An initial pilot phase of the program (Phase 1) was implemented in October of 2013 among approximately 2,000 households[69]. Following the completion of several studies in Phase 1, including a health impact randomized controlled trial[49], a large-scale (Phase 2) program among approximately 102,000 households was implemented between September and December of 2014 in Rwanda's Western Province. The program included the distribution of the EcoZoom Dura improved wood burning cookstove and the Vestergaard Frandsen LifeStraw Family 2.0 household gravity-fed water filter. The intervention includes household level education and behavior change messaging to each household through MOH Community Health Workers. Currently, the program includes educational promotion activities as well as repair and replacement services throughout program households[77].

Methods

This analysis examines the costs and benefits of the *Tubeho Neza* Phase 2 program over a projected period of ten years and is informed by field survey data, kitchen performance tests and controlled cooking tests, as well as two years of experience with the program implemented at-scale. Similar studies have been conducted on cookstove programs[13–16] and drinking water interventions[38] separately, but the authors are not aware of any cost-benefit analysis of a combined program. The cost-benefit model was designed based on the methodology outlined in the aforementioned referenced studies, with additional guidance from World Health Organization documents for conducting cost-benefit analyzes of household energy, and water and sanitation interventions[78,79]. Presumed benefits include those related to livelihood and environmental impacts associated with the water filter and improved cookstove technologies implemented within the *Tubeho Neza* program. Impacts related to health were not considered in this study as a related study is currently being conducted to quantify this impact. As this study examines an already implemented and on-going program, the analysis was informed by data collected from field studies and program details (Table 1). Additional assumptions necessary for the analysis are outlined.

Table 1. Overview of data sources.

Study or Source	Citation	Description	Data Source Used in Analysis
Verification Survey	Barstow et al., submitted for publication	1st survey round - two-stage cluster sample, 320 villages, 960 households 2nd survey round - simple random sample, 187 households	Initial filter and stove uptake Estimated decrease in adoption rates over time
Sensor Based Monitoring	Thomas et al., submitted for publication	Randomized controlled trial - simple random sample, 168 households in each study arm	Lower and upper range of adoption rates
Program Description	Thomas, 2015	Overall description and projections of Tubeho Neza program	Programmatic Cost Estimates
Kitchen Performance Test	Present study	Cross-sectional study - two-stage cluster sample, 32 villages, 96 households in each study arm	Stove fuel consumption Fuelwood price Fuelwood collection time
Controlled Cooking Test	Present study	Nine tests - 3 households in triplicate	Water boiling fuel consumption Water boiling time
Forestry Studies	FAO, 2007 Ministry of Natural Resources Rwanda, 2014	Forestry reports and guidelines	Average biomass density in Africa Tree density in Rwanda
Carbon Credit Methodology	Clean Development Mechanism, 2015	Small scale methodology for energy efficiency measurement in thermal applications of non-renewable biomass	Certified emission reduction assumptions and equations
DelAgua Program of Activities	UNFCCC, 2013	Description of certified emission reductions for the *Tubeho Neza* program	Program specific certified emission reduction calculations

Intervention Program Metrics

Technology Adoption Quantification

The "verification" survey, conducted by the implementer to meet the United Nations Clean Development Mechanism requirements for carbon credit issuance, a primary form of revenue to support the program, was used to quantify initial uptake and adoption values for cookstoves and water filters. The first verification, conducted in 2015 approximately six weeks to six months after distribution of the products reported the EcoZoom stove as the primary cookstove among 92.8% of households while the LifeStraw water filter was reported as the water treatment method among 95.4% of households. The second verification survey, conducted approximately ten months to one year after distribution reported a 3.5% decrease in households reporting the EcoZoom as their primary cookstove and a 4.0% decrease in households reporting the LifeStraw as their water treatment method[69]. Initial uptake of the cookstove and water filters, as reported during the first verification survey, was used as the percentage of the population benefiting from the technologies during year one, while adoption was assumed to decrease each year by values reported in the second verification up to year five, at which point adoption values were assumed to stabilize following the replacement of products in year six.

To assess uncertainty in the adoption rates, a range of filter and stove adoption values were modeled. An electronic sensor based monitoring activity was conducted in a parallel study wherein a sample of filters and stoves were instrumented with sensors measuring actual usage of the technologies. Sensor based measurements may provide more objective values because they do not rely on survey based data which can be biased[60]. The study reported a stove adoption rate of 73.2% and filter adoption rate of 90.2%[80].

Kitchen Performance Test

The kitchen performance test (KPT) is comprised of two components; the measurement of household fuel consumption over multiple days and a quantitative survey to characterize fuel consumption and cooking practices. The KPT is performed within households where they are asked to prepare and cook meals as they normally would. Enumerators visit a household for four consecutive days, measuring the amount of fuel consumed for three 24-hour periods with weight scales. Daily consumption over the three days is averaged and fuel consumption per person is calculated using a standard adult equivalence factor to obtain a normalized household size[59]. The quantitative survey developed for this study included approximately 75 questions and takes about 45 minutes to administer. Questions primarily relate to a household’s cooking and fuel procurement methods as well as socioeconomic indicators. The survey was piloted extensively including a two day classroom training with enumerators and field based practice surveys in households.

A cross-sectional study was chosen as a randomized control trial (RCT) was being conducted for a parallel study and thus a control group of approximately 40,000 households had been previously identified. Intervention households were chosen from the implementer’s distribution list of approximately 102,000 households while control households were chosen from the list of control households which will eventually be used for distribution of products upon completion of the RCT. A two-stage, cluster sample design was used whereby 32 villages were randomly selected from both groups using probability proportionate to size sampling and then three households randomly selected within each village using simple random sampling, resulting in a sample of 96 households in both the intervention and control groups. Households that could not be found, did not consent or did not have an adult over the age of 18 responding were not surveyed and the next household in the randomly generated list was visited.

Descriptions of particular metrics derived from the KPT study are outlined in relevant sections below. Primarily, the fuel consumption results are used throughout the study where average per capita fuel savings were calculated as the difference between the control and intervention fuel consumption.

Controlled Cooking Test

To quantify fuel savings from the water filter, a controlled cooking test (CCT) was conducted[81]. The CCT is a field based test where a household is asked to perform a specific cooking task as they would under normal conditions. Fuel used during that specific task can then be measured. In this case, three households in the KPT control area who normally boil their water for drinking were asked to boil water three times as they typically would and the amount of fuelwood used was measured. The volume of water was measured and households were asked questions related to their water treatment practices.

Cost Estimation

The cost of the program was quantified through an incremental cost analysis where intervention costs are separated into capital costs and recurrent costs. Investment costs describe all intervention costs incurred at the beginning of the intervention including the cost of the hardware and the administrative and implementation costs. Recurrent costs are those which occur periodically throughout the lifetime of the program including product maintenance and educational outreach activities. Given both technologies have an estimated lifetime of five years and the length of this study projects to ten years, the capital cost was estimated to occur in both year one and year six assuming a replacement of all products still in use after year five. The capital cost was reported as $30 per stove and $30 per filter, while the recurrent cost was reported as $5 per stove and $5 per filter[82].

To account for the differential timing of costs, a commonly used discount rate of 3% is applied to all costs and benefits occurring after 2014. The model also examines at 0% and 5% to assess uncertainty. The net present value (NPV) can then be calculated using the following formula:

$$NPV_{costs} = \sum_{t}^{T} \frac{costs}{(1+r)^t}$$

where $\sum(t, T)$ is the sum of all costs at time periods from t=0 to the end of the intervention T=20 years, and r is the discount rate.

Impact Estimation

Three impacts were analyzed for both the improved cookstove and water filter: fuel savings, time savings and environmental benefits.

Improved Cookstove Impacts

Fuel Savings

To quantify fuel savings from the improved cookstove over a ten-year period, the savings in per capita fuelwood usage measured in the KPT study was multiplied by the total population of the intervention. The total fuelwood savings was then only applied to the population reporting the stove as their primary cookstove (92.8%), with the cookstove adoption decreasing yearly by 3.5% until year five. The average price of fuelwood reported during the KPT survey was then used to monetize the fuelwood savings with the minimum and maximum fuelwood prices additionally examined to assess any uncertainties in this value.

Time Savings

Time savings from the improved cookstoves were estimated from household's reported reduced time collecting firewood attributable to fuel savings. Survey results indicated that of the households which primarily collect fuelwood (74.3%), 93.1% reported a decrease in time collecting wood with 74.1% of reported activities with the extra time related to agriculture or other income related activities. Thus time savings were assumed based on the time to collect fuelwood.

To estimate the actual time saved, the reported time to collect one bundle of fuelwood was then converted into a total time savings based on fuelwood saved between control and intervention groups, among the fraction of households which collect fuelwood. Similarly to the fuel savings calculations, adoption of the cookstove was assumed to decrease by 3.5% per year up to year five. Monetization of the time savings was calculated by taking the average hourly labor rate reported in the KPT survey. Additional analysis was conducted to determine the effect of the hourly labor rate by evaluating the model at the minimum and maximum reported labor rates.

Environmental Benefit

The environmental benefit of the cookstove was assessed based on two metrics: locally from reduced deforestation and globally, attributable to reductions in carbon emissions.

Deforestation has been quantified in the literature by estimating the cost of replacing any forest cover that would be lost were the intervention not in place[14–16]. Both the cost of the tree saplings and the labor to plant them was calculated for this study. The total mass of fuel saved was converted to area of forest cover using the average biomass density in Africa (109 tons/ha)[83] whereby the labor necessary to plant one hectare was measured in surveys and informal interviews. Additionally number of tree saplings was estimated based on area of forest cover by the tree density of Eucalyptus in Rwanda (1350 trees/ha)[84] and monetized based on locally reported costs of Eucalyptus tree saplings. A common wastage factor of 30% was applied to account for wood species that would be unusable as fuel[14,15].

Carbon emissions were estimated using the Clean Development Mechanism for Small Scale Projects methodology[85]. Emission reductions are calculated using the following formula:

$$ER_y = B_y * f_{NRB,y} * NCV_y * EF_{biomass}$$

Where ER_y is the emission reductions during a specified year y measured in tons of CO_2 emissions (tCO_2e), B_y is the quantity of woody biomass that is substituted or displaced in year y, $f_{NRB,y}$ is the fraction of non-renewable biomass used in the absence of the project activity in year y (0.98 default value for Rwanda), NCV_y is the net caloric value of the non-woody biomass that is substituted (0.015 TJ/tonne recommended default value for wood fuel) and $EF_{biomass}$ is the emission factor for biomass fuels (methodology specifies using 81.6 tons CO_2 per TJ of wood)[85]. The quantity of woody biomass (B_y) is calculated using the following formula:

$$B_y = B_{baseline} * LF * \left(1 - \frac{n_{traditional}}{n_{improvedstove}}\right) * BU_{baseline} * UF * AF_{improvedstove}$$

Where $B_{baseline}$ is the fuel used per person before the intervention (327.54 kg/person/year)[19], LF is the leakage fraction to account for non-renewable biomass saved by the intervention (0.95)[85], $n_{baseline}$ is the efficiency of a traditional stove (10%), $n_{improvedstove}$ is the efficiency of the improved stove (38%)[54], $BU_{baseline}$ is the fraction of the intervention population which used biomass as their fuel source before the intervention (99%), UF is the fraction of total cooking performed on the improved stove (0.85) by accounting for stove “stacking” behavior where the household continues to use the traditional stove alongside the improve stove, and

$AF_{improvedstove}$ is the fraction of the population which has adopted the improved stove. Additionally, because the intervention includes the water filter, the baseline fuel used ($B_{baseline}$) was reduced from 377.54 kg/person/year to 327.54 kg/person/year to account for carbon credits claimed from the reductions in boiling water for drinking[55]. Total emission reductions was then monetized based on a historical price of certified emission reductions for the African region, in October of 2015 when the first carbon credits for the program were issued (\$5.40 per ton CO_2)[86]. As the price of carbon can vary significantly based on a number of factors the model was assessed at a low carbon credit price of \$1 to a high carbon credit price of \$30. These values capture typical current carbon credit prices[87].

Water Filter Impacts

Fuel Savings

Any fuel savings attributable to the filter is assumed to be realized only be among households who previously boiled their drinking water. 26.6% of intervention households reported treating their water in some method before receiving the water filter with 80.7% of these households reporting boiling their water. This suggests that 21.4% of households in the intervention reduce their actual fuel usage due to switching from boiling water to the water filter. The authors acknowledge that this generalized estimate has not been rigorously evaluated as some experts indicate that actual fuel savings from water filter interventions may be de-minimus[88]. The controlled cooking test results were used to quantify total fuel savings per person each year. Regardless, for the purpose of generalized estimating, total fuel savings is then calculated based on the population of the intervention, the percentage of the population who boiled water before receiving the filter, the percentage of the population who adopted the filter with a 4.0% reduction in filter usage each year up to year five, and the fuel usage for a boiling event from the CCT.

Similar to fuel savings from the improved cookstove, the total fuel savings from use of the filter was monetized using the average price of fuelwood.

Time Savings

Time savings from use of the filter was calculated based on the reduced time needed to collect wood from no longer boiling and the time used while boiling the water. Time savings from wood collection was calculated identically to the improved stove calculation with the exception of the fuel savings based on the CCT. The time necessary to boil water was additionally measured during the CCT and resulted in a time savings of 402 minutes/person/year. Both time savings were again monetized using the average labor rate.

Environmental Benefit

As estimated for the improved cookstoves, the environmental benefit of the water filters was assessed at both the local and global scale.

Local estimations based on reduced deforestation were performed as outlined for the improved stove with fuelwood reductions estimated from the amount of wood used for boiling as measured from the CCT.

At the global scale, greenhouse gas emissions for the water filter are calculated using the following formulas based on the carbon credit methodology:

$$ER_y = BE_y - PE_y - LE_y$$

Where BE_y is the baseline emissions in year y, PE_y is the project emissions (0 tCO2/year due to no on-site consumption of fossil fuels and electricity due to the project activity), and LE_y is leakage emissions in year y.

Baseline emissions and leakage emissions are calculated using the following formulas:

$$BE_y = QPW_y * m * X_{boil} * SEC * \sum_i (BLfuel, i * f_{NRB} * EF_{projectedfossilfuel,i} * 10^{-9}$$

$$LE_y = LF * BE_y$$

Where QPW_y is the total quantity of purified water per filter per year (2609.8 liters), m is the fraction of households which are not already served by a safe drinking water source (0.99), X_{boil} is the fraction of the population which would have boiled water for drinking before the intervention (default to 1), SEC is the specific energy consumption to boil one liter of water (3574.8 kJ/L ^{o}C based on the baseline stove efficiency of 10%), and $BLfuel, i$ is the proportion of the baseline which uses firewood (0.99).

Cost-Benefit Analysis

In order to compare cost and impact estimations, a simple cost-benefit ratio (CBR) was calculated.

To examine uncertainty, a sensitivity analysis was performed using Oracle Crystal Ball which uses the Monte Carlo method[89]. The six variables assessed for their effect on the overall analysis as outlined in the previous sections include: discount rate, filter and stove adoption, price of fuelwood, value of labor and carbon credit value.

Ethics and Consent

The Rwanda National Ethics Committee (IRB #206/RNEC/2015) approved the protocol including all questions and the consent procedure. Additional approval was received from the University of Colorado Institutional Review Board (Protocol #: 15-0613). Each household enrolled provided informed, verbal consent after receiving details regarding the purpose of the survey. All respondents were over the age of 18. Consent was administered through a smartphone based survey with all records stored on a password protected server. Participants were given the opportunity to ask questions before consenting to participate. Additionally all households, regardless of consenting to the surveys were able to retain the filter and cookstove.

Results

Kitchen Performance Test

The KPT measured control household fuel consumption as 810.8 kg/person/day while intervention households consumed 527.4 kg/person/day, a 35.0% savings. Thus fuelwood savings were assumed to be 283.4 kg/person/day throughout the calculations. An important note is that the KPT fuel savings estimates are inclusive of “stove stacking” behavior wherein some households continue to periodically use their baseline stoves for some cooking events. Therefore, the KPT wood fuel savings estimate does not assume a total switch to the intervention stove.

Controlled Cooking Test

Households which reported boiling water as a treatment method, reported boiling an average of 2.17 liters per person per week for drinking water. Households typically boiled in five liter batches which consumed an average of 3.03 kg of wood per boiling event. An average fuel consumption could then be calculated as 72.5 kg/person/year. The average time to boil the five liter batch was 18 minutes resulting in an average yearly time consumption from boiling of 402 minutes/person.

Program Cost

The total cost of the program over a ten year period with a 3% discount rate is estimated around $16.5 million with an estimated cost per household of approximately $160. About 37% of costs are incurred during the initial implementation in year one and another 26% in the replacement period in year six. Maintenance and repair costs incurred during years 2-5 and 6-10 represent around 5% per year of the total cost.

Impact Analysis

Figure 1 summarizes the estimated impacts of the intervention. The total monetized benefit from the ten year intervention is estimated over $129 million at approximately $1,270 per household, with over 92% ($119 million) of benefits attributable to the cookstoves. Fuelwood savings from both products account for the majority of total benefits (80%), with 95% of fuelwood savings coming from the estimated 1.18 million tons of fuelwood saved by the cookstove. Environmental impacts account for 12% ($14.6 million) of the benefits with 57% from local reductions in deforestation with the remainder from reductions in carbon emissions. The water filter contributed approximately 20% of the environmental benefits. Finally, benefits from time savings accounted for only 8% of total benefits, with cookstoves again providing the majority of the time savings benefits (88%).

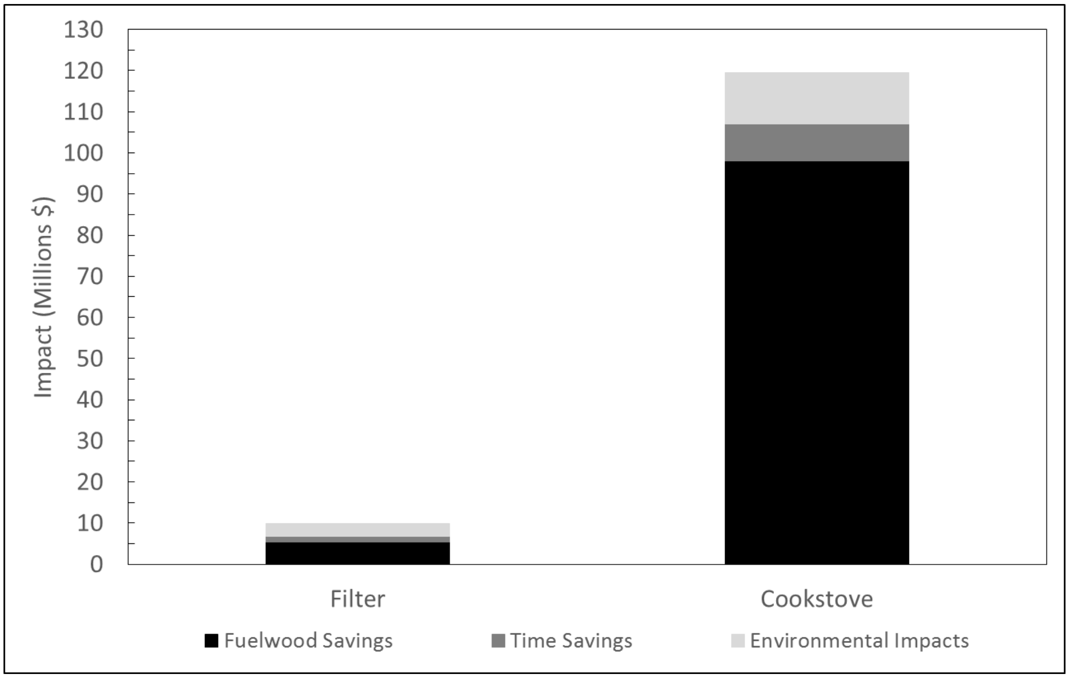

Figure 1. Monetized benefits of water filters and improved cookstoves.

Cost-Benefit Ratios

A CBR of 7.8 was estimated for the cookstove and water filter intervention. Overall, fuelwood savings was the primary contributor to the projected CBR. Contributions from time savings equated to only 8% while environmental impacts contributed 12%. The cookstove provided the majority of all benefits (92%), contributing 95% of fuel savings benefits, 88% of time savings benefits and 80% of environmental benefits.

The sensitivity analysis indicated a CBR range of 1.5 to 21 based on the low and high range scenarios (Table 2). The six inputs which were varied, ranked in the following order based on their sensitivity within the cost benefit model: fuelwood price, value of labor, carbon credit price, stove adoption rate, discount rate and filter adoption rate.

The price of fuelwood was the primary contributor to variability in the model. Varying only the price of a wood bundle to the minimum reported price of $0.42 per bundle reduces the cost benefit ratio by 64% to 2.8 while valuing the fuelwood at the maximum price of $4.17 per bundle increases the cost benefit ratio by 80% to 14.1.

The value of labor provides the next most significant contribution with the minimum reported cost of labor ($0.02/day) only reducing the CBR to 7.1 because of the already low $0.12 daily labor rate but increasing the CBR to 11.9 based on the maximum reported cost of labor ($0.69/day). A similar trend is seen with carbon credit pricing with a CBR range of 7.5 to 9.6 based on minimum and maximum values due to the expected price of carbon being closer to the minimum value assessed.

The lower-end stove adoption estimate had a more significant impact on the projection than the filter adoption estimates, a change in approximately 15% for the stove and only 2% for the filter, due to the lower adoption among stoves and the higher contribution of stove benefits generally. Notably, the cost benefit ratio actually increased with the lower filter adoption rate. Because the contribution of the filter benefits is so minimal, the lower cost of filters outweighs the benefits

Varying the discount rate had little effect on the overall CBRs. An approximately 1% reduction or increase was estimated based on a 5% and 0% discount rate.

Table 2. Estimated cost benefit ratios for the expected, best and worst case scenarios of the cost benefit analysis.

	Cost Benefit Ratio		
Impact Category	**Assumed**	**Lower Range**	**Upper Range**
Total Stoves	7.2	1.4	19
Fuelwood Savings	5.9	0.98	12
Time Savings	0.55	0.075	3.3
Environmental Impacts	0.75	0.32	3.0
Total Filters	0.59	0.13	2.1
Fuelwood Savings	0.33	0.067	0.68
Time Savings	0.077	0.013	0.46
Environmental Impacts	0.19	0.050	0.99
Program Total	7.8	1.5	21

Discussion

Previous improved cookstove and water treatment studies have reported similar CBRs as those estimated in this study. Evaluations of cookstove programs in Uganda[15], Malawi[16] and Mexico[14] reported CBRs ranging from 3 to 29. While two of three of these studies included an estimation of health benefits, all studies estimated fuelwood savings as the dominant contributor to the program benefits, similar to this study. A cost-benefit analysis of global interventions in the water supply and sanitation sector[38] reported CBRs from 4 to 32, with CBRs from 5 to 41 when providing universal basic access to improved water and sanitation as well as point of use water treatment through use of chlorine.

An estimated 1.18 million tons of total fuelwood will be saved over the ten year lifetime of the program, equating to approximately 11.6 tons per household. Fuelwood savings from the improved cookstove alone provide benefits almost six times the cost of the program with the fuelwood savings from the water filter being the primary driver of water filter benefits. While environmental impacts accounted for only 12% of the total CBR, a 2013 study prepared by the Rwanda Ministry of Natural Resources examined the woodfuel supply and demand nationally. In the Western Province, the location of the intervention under study, the "business as usual" projected woodfuel demand in 2020 is estimated at 1.165 million tonnes per year, while the supply is estimated as 1.058 million tonnes – an annual deficit of 106,000 tonnes, indicating an unsustainable deforestation rate absent mitigating interventions[90]. While this program is not the only woodfuel reduction intervention being pursued in this region, the present study estimates that, with over 102,000 households reducing woodfuel use by 35% in year 1, approximately 120,000 tonnes of woodfuel savings in the Western Province may currently be attributable to the program, decreasing to 102,000 tonnes in 2024. These estimates suggest that this program alone can more than compensate for the projected regional woodfuel deficit.

Additionally, while time savings provided less than 10% of the overall benefits, households who collect fuelwood may save approximately 48 days per year collecting fuelwood while households who previously boiled may save approximately 23 days not performing the task of boiling water for drinking.

While the sensitivity analysis provided a large range of potential CBRs, between 1.1 and 15, the fuelwood price was the largest contributor to the uncertainty. However, little variance was measured between reported fuelwood pricing, and thus a high degree of certainty can be placed in this variable.

The value of labor was the next most significant variable mostly due to its inclusion in both the time saving and deforestation calculations. The value of time is a debated topic because of the uncertainty in both how much time is actually converted to income generating activities and the actual value of the time. In this study, the majority of households reported using the additional time for income generating activities. Additionally, only the time collecting wood was quantified and no contributions from time saved cooking were quantified, thus the estimate was considered conservative. The value of labor was calculated based on reported wages from surveyed households instead of an average wage from the national income survey due to the lower economic status of the intervention households.

While the carbon credit price is not a large determinate in the CBR estimates, it is likely the most volatile of the variables. The value of carbon credits has decreased significantly over the past several years and continues to be unpredictable on both the voluntary and compliance markets.

Generally, the water filter provided few non-health benefits in the context of this study. In fact, when analyzing the model at a lower filter adoption rate the CBR increased because the savings in filter cost outweighed the reduction in benefits. However, as described in the health impact studies from this program, the health impacts of the water filters are expected to exceed those from the stoves[49,82].

In addition to the environmental benefits estimated in this paper, there is an emerging alignment between monitored health impacts, calculations of units of heath impact (Averted Disability Adjusted Life Years – ADALYs), and, finally, monetized payments associated with demonstrated ADALYs. These estimates can provide additional input to cost-benefit evaluations. The WHO CHOICE guideline suggests that any intervention that costs less than three times the per capita GPD per each ADALY is cost effective. Generalized estimates of ADALYs generated from both diarrhea reduction and particulate matter personal exposure reduction among children under 5 suggest significant cost effectiveness associated with the water filter intervention, potentially balancing the environmental impacts realized by the cookstoves[82].

Conclusion

From a cost-benefit perspective, this study suggests that this intervention provides significant benefits, comparable to similar studies. Most significantly, this program may potentially be responsible for addressing a regional woodfuel deficit. Even in the conservative case scenario modeled in the sensitivity analysis, the benefits still outweigh the total cost of the program. Fuelwood savings alone, mostly from improved cookstoves, provide substantial evidence to support the implementation. However, while this study and many others have shown a positive benefit to cost relationship, the authors recognize that many variables within this study, specifically usage rates, are going to be program dependent and thus the results of this analysis are not necessarily transferrable to all improved cookstove or water filter interventions.

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Conflict of Interest Disclosure

Authors Barstow and Thomas are compensated consultants to the funder, DelAgua Health. Their responsibilities include designing and delivering the intervention described. Authors Linden and Bluffstone are compensated researchers.

Study 4: Assessing Improved Cookstove Sustainability: An Evaluation of Locally Manufactured and Imported High Efficiency Rocket Stoves in Rwanda

Barstow CK, Linden KG, Thomas EA, Mugabo L, and Cook S. (2016) Assessing Improved Cookstove Sustainability: An Evaluation of Locally Manufactured and Improved High Efficiency Rocket Stoves in Rwanda

Abstract

Improved cookstoves have the potential to reduce a wide range of health issues including acute lower respiratory tract infections, COPD and pneumonia. Additionally, cookstoves can provide a variety of other benefits including environmental impacts through reductions in greenhouse gas emissions and economically through reductions in expenditures on fuelwood. In Rwanda, improved cookstoves may help reduce the 12,000 deaths each year from indoor air pollution, decrease the deficit in sustainable availability of firewood and provide cost savings to the majority of households which use fuelwood for cooking. However, a wide range of cookstove designs are available and choosing the correct technology for a specific program can be challenging. Specifically, deciding whether to import a stove or produce it locally can be a fundamental program decision. In this study, we evaluated the overall sustainability of an imported and a locally made stove which are both currently available in Rwanda. Both stoves were evaluated based on environmental, economic and social sustainability metrics to determine important factors in an overall sustainable stove design. From an environmental perspective, stove efficiency was the primary factor with use phase emissions contributing most heavily to the analysis. Social sustainability was evaluated based on several metrics including health but

neither stove met WHO health standards. Economic sustainability was measured using cost effectiveness whereby the wood procurement method determined if either stove was cost effective. In the scenario of households which collect wood, and thus having no on-going costs, both stoves were cost effective, but when households had to purchase stoves, the on-going costs outweighed the health benefits. Overall, a hybrid stove model which can integrate some aspects of local manufacturing while not sacrificing stove efficiency and emission reductions will be necessary to create a more sustainable stove design. However, keeping costs low to meet economic sustainability metrics will be challenging under this scenario.

Introduction

Advocacy and provision of improved cookstoves has become a high priority for developing world countries with international attention and resources being pulled into the cookstove sector. Much of the driving force comes from the Global Alliance for Clean Cookstoves' goal of reaching 100 million households by 2020 with clean cookstoves [91]. Improved cookstoves have the potential to reduce a range of serious health issues (including acute lower respiratory tract infections, chronic obstructive pulmonary disease and pneumonia) which have been estimated by the World Health Organization to significantly contribute to the annual death of more than 4 million people worldwide [92]. Improved cookstoves can also provide environmental benefits from the reduced amount of biomass required for cooking and reduced carbon emissions, and economic benefits because of their potential to reduce expenditures on purchasing fuelwood and charcoal[93].

In Rwanda, implementations of improved cookstove programs could help to reduce the high level of indoor air pollution (IAP) which accounts for over 12,000 deaths per year [3] and the 18% of pneumonia-related deaths of children under five [17]. In a country of nearly 10.5 million people, of who over 82% depend on firewood as their main source of energy for cooking [65], decreased wood demand from improved cookstoves could help reduce the deficit in sustainable availability of firewood [19]. Additionally with approximately 80% of Rwandans living on less than $2 per day [20], cost savings from improved cookstoves have the potential to benefit individual households daily expenditures. The Rwandan government, recognizing the importance of this issue, aims to reduce the wood consumption to less than 50% of the national energy consumption by 2020 [94] and deliver 400,000 improved cookstoves to rural communities [95].

However, with a wide range of possible cookstove interventions available, several factors such as quality, usability, affordability, scalability and reduction in IAP emissions should be weighed in the implementation of a sustainable cookstove program. One important decision which frequently arises is whether to import or produce stoves locally. Importing stoves can provide higher quality control and performance through more advanced designs and mechanized mass production while local production can provide employment opportunities and build capacity within the region.

To better understand this choice, a sustainability analysis was performed to compare the environmental, social and economic factors associated with an imported or locally made improved cookstove. In this study, two existing improved cookstove technologies in Rwanda, one imported and one manufactured locally, were compared to provide insight into factors which could affect the overall sustainability of a cookstoves program. The purpose of this study is to compare the actual cookstove hardware and does not assess any programmatic models used to implement these cookstoves.

Improved Stove Models

EcoZoom Dura

The EcoZoom Dura is the imported cookstove examined in this study. The EcoZoom Dura is manufactured in Shengzhou, China with raw materials, primarily metal and ceramic, being sourced in China. Full assembly of stoves are shipped from China to Tanzania and further transported by road from Tanzania to Rwanda. The design of the stove is based on the rocket stove concept where an insulated combustion chamber channels air flow to create a more complete burn[96]. The stove includes a "stick support" where fuelwood is placed to promote air flow and a "pot skirt" which increases thermal efficiency by channeling heat to the bottom and sides of the pot. Laboratory based studies rated the EcoZoom Dura at a thermal efficiency of 38.1%, placing it in the tier 3 efficiency category of the International Standard Organizations (ISO) benchmark guidelines[54], with a separate laboratory study conducted on a previous version of the EcoZoom stove (StoveTec GreenFire), showing an almost 50% reduction in carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) over the traditional 3-stone fire[97]. Water boiling tests performed in Rwanda also measured a nearly 50% reduction in fuel use over the 3-stone fire[98]. The EcoZoom Dura has been disseminated by DelAgua, a social enterprise, in partnership with the Rwanda Ministry of Health to approximately 100,000 households in the Western Province of Rwanda[77].

Canarumwe

The locally produced stove is the *Canarumwe* stove. *Canarumwe* stove liners are adapted from a stove previously implemented in Kenya (*Upesi*) to be produced entirely locally in Rwanda by potter cooperatives[99]. The stove liners are made from a mixture of clay, sand, stone and water which is shaped by use of a standard mold and then fired in a kiln to cure as ceramic. The liners are typically installed in a fixed hearth using mud, bricks or stones. Thermal efficiency in the laboratory was measured as 26.3%, placing it in the tier 1 ISO efficiency category[100] while a field study measured a fuel use reduction of 49% over the 3-stone fire[101]. Tens of thousands of *Canarumwe* stoves have been sold in nearly all 30 districts of Rwanda with hundreds of cooperatives members trained to manufacture, distribute, install and sell *Canarumwe* stoves. The Rwandan Ministry of Infrastructure and The Water and Sanitation Corporation, with support from Practical Action Consultancy, SNV and Inclusive Business and Consultancy Ltd., has promoted the stove cooperatives through development of local and decentralized production and distribution[99,101].

Methodology

Data Collection Methods

The analysis performed throughout this study is primarily based on a literature review of publicly available journal articles and reports. However, available data was not always sufficient and thus a limited amount of data was collected through informal interviews, questionnaires and field based water boiling tests. Additional assumptions and extrapolations were necessary and are explained throughout this section and in the supporting information.

Informal Interviews and Questionnaires

Manufacturers of both the imported and locally made cookstoves were asked for additional information on the raw materials and processes used to produce the cookstoves. The imported stove manufacturer provided information on material properties and assembly processes used at the manufacturing facility in China. Questionnaires were administered to members of six of the locally made stove cooperatives which included details of raw material acquisition, protocols used for producing stoves, cooperative membership and participation, pricing, marketing and stove sales.

Environmental Assessment

Environmental metrics were evaluated using a life cycle assessment (LCA) approach whereby environmental impacts associated with each life cycle phase of the stoves is quantified. Stoves were evaluated from raw material extraction, to manufacturing and processing and finally to the use phase. The waste disposal or recycling phase was not included in this analysis due to the uncertainty of the end-of-life for the stoves. Stoves were analyzed using SimaPro LCA software[102], utilizing the ecoinvent database[103] and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) method[104]. The TRACI method uses a midpoint oriented assessment approach which characterizes impact categories. Ten environmental impact categories are analyzed in the TRACI method: ozone depletion, global warming, smog, acidification, eutrophication, ecotoxicity, fossil fuel depletion, carcinogenics, non-carcinogenics and respiratory effects. Given both stoves have reported a lifetime of up to five years[99], the functional unit was conservatively defined as the use of each stove for four years in a single Rwandan household. Figure 1 shows the system boundaries for the cookstoves.

Details of raw materials, production processes and transportation were gathered from existing reports, data provided by EcoZoom and the cooperative questionnaires. Additional assumptions were necessary in order to appropriately utilize the ecoinvent database which are outlined in the supporting materials.

The impact of the usage phase for each stove was approximated based on fuelwood and emission reductions reported over a three stone fire. Three stone fire usage was assumed to be 1888 kg per household per year[19] with the imported stove reducing wood usage by 65.8%[69] and emissions by 50.6%[97], and the locally made stove reducing wood usage by 50%[101] and emissions by 26.2%[97].

Social Assessment

Social sustainability was evaluated using four metrics: health, quality control, scalability and local capacity building. Both quantitative and qualitative methods were utilized in analyzing these metrics.

Health

To quantify health, avoided deaths and averted disability adjusted life years (DALYs) were calculated using the Household Air Pollution Intervention Tool (HAPIT). DALYs convey the number of years lost to illness, in this case from diseases caused from indoor air pollution. HAPIT calculates averted DALYs by first extracting DALYs from the Global Burden of Disease based on Rwanda specific conditions. Relative risk is then derived for each disease from integrated exposure response curves using particulate matter ($PM_{2.5}$) exposure measurements. The attributable fraction is then calculated based on the percentage exposed to solid fuels and the relative risk. And finally averted DALYs are calculated as the DALYs by the attributable fraction[105].

Several inputs into the HAPIT model are required including personal exposure measurements, number of target households, fraction of target households using the stove and stove lifetime. The baseline and imported stove personal exposure were characterized through a recent field study[106]**. Unfortunately, no personal exposure data could be acquired for the locally made stove, and thus exposure was extrapolated based on a laboratory study of stove emissions[97]. The number of target households was set to 25,000 due to an upper limit set in the HAPIT model itself. The fraction of households using the stove was set to 100% for both stove scenarios given that the intent of the study was not to study adoption rates and stove lifetime was set to four years for both stoves as mentioned previously. Detailed assumptions, calculations and the output of the HAPIT model can be found in the supporting information.

Quality Control

To better understand consistency in quality from one stove to another, reproducibility in each stove production process was analyzed. Primarily informal interviews, cooperative questionnaires and existing reports were used to qualitatively examine the production process. Additionally, a field based water boiling test was used to quantitatively evaluate variance between the same stove models. The water boiling test (WBT) is a controlled test used to measure stove efficiency. WBTs were conducted in triplicate on five imported cookstoves and five locally made cookstoves to quantify the variance in thermal efficiency between the cookstove models. Imported cookstoves were taken from five different cookstove shipments representing production through several different months, while locally made cookstoves were acquired from cookstove cooperatives in five different Districts. Protocols outlined in *The Water Boiling Test, Version 4.2.3* were followed, though the tests were performed outdoors in Rwanda's capital, Kigali, instead of the protocol's intended laboratory based setting[107]. The F-test was used to determine if the thermal efficiency variance of the two stoves was equal.

Scalability

Both production processes were qualitatively analyzed to determine the plausibility and effort required to scale the production process to produce one stove for every household who uses fuelwood in Rwanda. Approximately 82% of Rwandan's 10.5 million people use fuelwood. With an average household size of 4.4 persons[108], 1.96 million stoves would need to be produced to serve this population.

Local Capacity Building

Similarly to the scalability metric, local capacity building generated in producing cookstoves for 1.96 million Rwandans will be examined. Given the EcoZoom is imported, no local benefits will be realized and thus this metric will primarily assess the possible local capacity created by the *Canarumwe* stove.

Economic Assessment

To evaluate economic sustainability, cost effectiveness of each stove was characterized. Cost effectiveness was calculated as the ratio of annual cost per DALY to the gross domestic product (GDP) per capita. The World Health Organization's Choosing Interventions that are Cost-Effective (WHO CHOICE), defines interventions which cost less than the GDP/capita as very cost effective and those less than three times the GDP/capita as cost effective[109]. The HAPIT model was again utilized to quantify cost effectiveness with the additional inputs of the capital cost of the stoves and the annual maintenance and fuel cost of each stove, in addition to the inputs outlined in the Social Assessment section to obtain the DALY measurement. The yearly stove maintenance cost was neglected for both stove scenarios as both stoves report lifetimes longer than the four years analyzed here and maintenance costs would be highly dependent on programmatic decisions. Two scenarios were analyzed in the case of an annual fuel cost, one based on households who only collect wood and the other based on households who only purchase wood. In the case of the wood collectors, no annual cost was realized, while in the wood purchasing scenario, yearly fuel cost was calculated based on fuelwood reductions from a three stone fire outlined in the Environmental Assessment section by the market price of a kilogram of wood.

Results and Discussion

Environmental Sustainability

Figure 1 shows the environmental impacts of the imported and locally made stoves based on the ten impact categories analyzed. Additionally shown are the contributions of the different phases in the life cycle process.

The primary finding is the large contribution of the use phase to the global warming, smog and acidification impacts. For both stoves, raw materials, production and transportation contribute less than 8% of total impact from these three metrics with the burning of fuelwood during actual usage of the stoves being the most significant contributor. The air emissions from the large amount of fuelwood burned during the four year lifetime of the stoves, over 2,500 kg for the imported stove and over 3,700 kg for the locally made stove, are responsible for this high impact. With the respect to the impact between the stoves, the imported stove has less than half the environmental impact because the imported stove is both more efficient and produces less emissions.

With regards to ecotoxicity and fossil fuel depletion the production and transportation phases become important factors. The locally made stove has almost no impact on ecotoxicity or fossil fuel depletion compared to the imported stove. Specifically the leachate from the production of steel in blast furnaces and basic oxygen furnaces creates the high impact on ecotoxicity. Approximately two thirds of contributions to fossil fuel depletion are from the energy used during the steel and ceramic production process with the remaining third from transportation of the stoves. Over a quarter of the total fossil fuel depletion can be attributed to road transportation from the port in Tanzania to Rwanda.

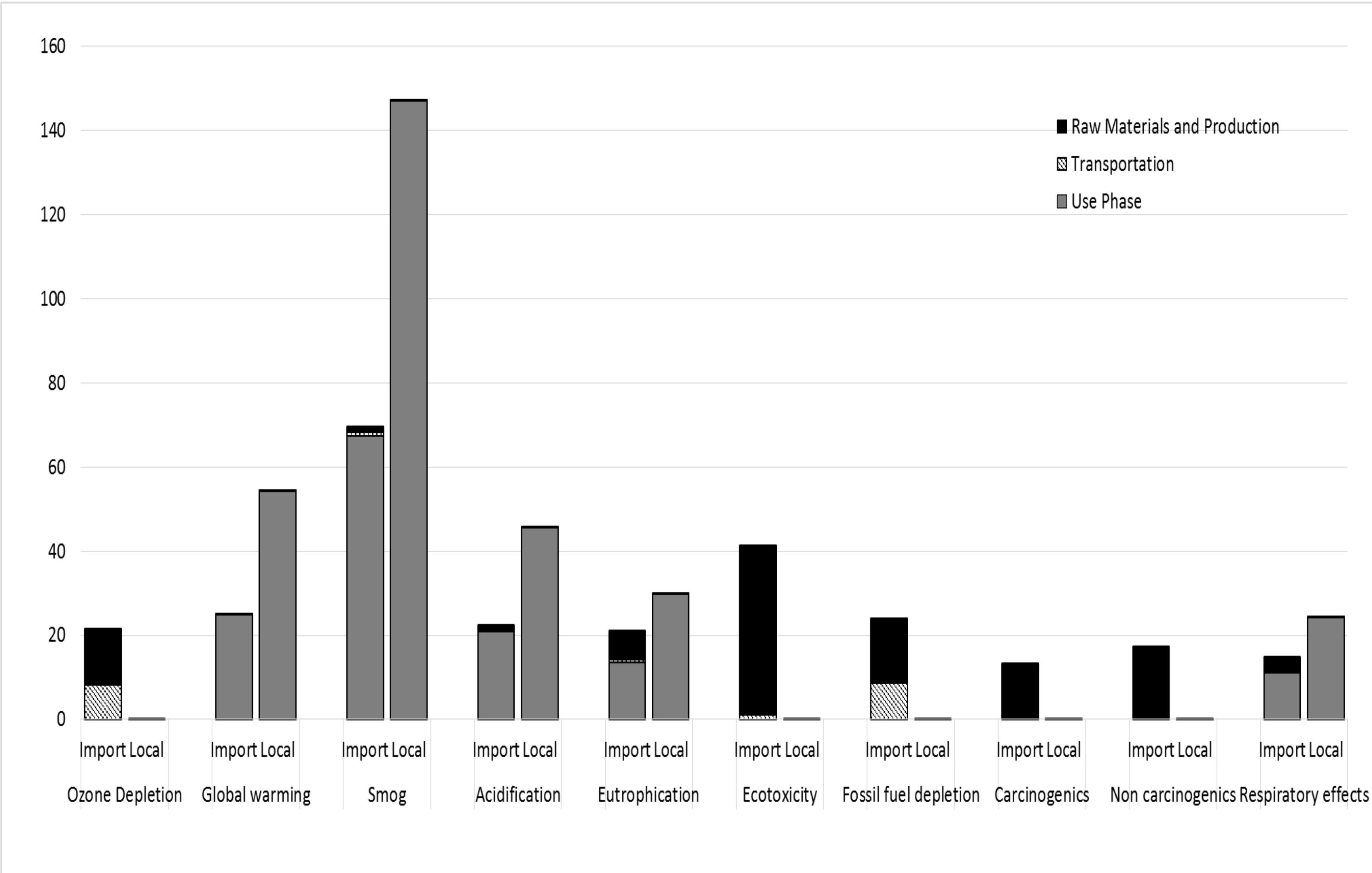

Figure 1. Estimated environmental impacts for the imported and locally made stoves: Ozone Depletion (x10^8 kg CFC-11, Global Warming (x10^{-2} kg CO_2 eq), Smog (kg O_3 eq), Acidification (x10 kg SO_2 eq), Eutrophication (x10^2 kg N eq), Ecotoxicity (x10^{-1} CTUe), and Fossil Fuel Depletion (MJ surplus), Carcinogenics (x10^6 CTUh), Non carcinogenics (x10^6 CTUh), Respiratory effects (*10^2 kg $PM_{2.5}$).

Social Sustainability

Health

Table 1 summarizes the primary health outcomes calculated from the HAPIT model. Averted deaths and averted DALYs are reported for both children under five and adults. Impacts related to children are calculated based on acute lower respiratory infections while impacts for adults are based on chronic diseases including chronic obstructive pulmonary disease, ischaemic heart disease, lung cancer and stroke[105]. Similarly to the environmental impacts related to stove emissions, the imported stove provides more health benefits than the locally made stove. While personal exposure was measured about 25% lower than the baseline for the imported stove and estimated about 10% lower for the locally made stove, the imported stove produces about 3 times more health impact than the locally made stove for both averted deaths and averted DALYs for both children under five and adults.

However, in order to meet World Health Organization (WHO) standards, personal exposure must be reduced to less than 10 ug/m^3, representing an over 95% reduction in personal exposure over the baseline scenario. Assuming the same number of target households, fraction using the stove and stove lifetime as the imported and locally produced stove, health impacts associated with reaching the WHO standard are around 20 times that of the imported stove and over 50 times that of the locally made stove. Thus neither stove provides substantial health gains in relation to meeting the WHO standard.

	Imported	Local	WHO Standard
Averted Deaths Children < 5	6.3	1.9	120.0
Averted Deaths Adults	4.2	1.4	118.0
Averted DALYs Children <5	540.0	193.0	11000.0
Averted DALYs Adults	193.0	69.3	3493.0

Table 2. Primary health outcomes for the imported and locally made stoves.

Quality Control

In large scale production of stoves, similar quality is necessary from one stove to another. The cold start thermal efficiency was calculated using the water boiling test method in order to study any variance between stoves produced through importation or local manufacturing. The F-test results indicated that the variance between the imported and locally made stoves was equal ($F_{import,local} = 2.47$, $p>.0005$). The result is surprising given all imported stoves are manufactured in the same facility with standards and metrics associated with large scale manufacturing. While the locally made stove is manufactured in cooperatives which use different clays and practices for producing stoves. Most cooperatives reported not using a precise mixture but could "feel" when the mixture was "scratchy" and ready. Additionally the firing process varied greatly between cooperatives and even within cooperatives between firings including some cooperatives using a kiln and others firing stoves on the ground and then covering the stoves with mud and grass. While the variance comparison didn't yield a significant difference between the stoves, qualitatively the variability between stove cooperatives provides uncertainty in the reproducibility of the locally made stoves.

Scalability

In order to provide one improved cookstove to all households who use wood as their primary fuel source, each stove production process was assessed for its ability to produce 1.96 million cookstoves. Based on current maximum production capabilities the imported stoves could be produced in approximately 2.3 years though its possible that the production could be scaled quicker by adding an additional shift. The maximum production of the locally made stove was modeled as one cooperative in all 30 districts producing the upper limit of reported capacity. Under these conditions, cooperatives could produce the needed stoves in approximately 4.5 years. Further scaling could be realized through the addition of more cooperatives but the training and initial set up of new cooperatives would require additional time and resources. Cooperatives also continually mentioned a shortage of wood and quality clay as limiting factors in production and thus these considerations would limit further cooperative expansion. Generally, scaling of the locally made stoves is likely possible but would require substantial inputs in training and management where the imported stoves could be scaled quickly and would likely not be vulnerable to material shortages.

Local Capacity Building

One of the primary drivers for local production is the creation of local jobs and capacity within the target population. During the production and manufacturing stages of the stoves lifetime, the imported stove will provide no benefits with respect to this metric. However, the locally made stove was analyzed for its potential benefits in building Rwanda's capacity. Profits to individual stove makers varied highly across cooperatives with cooperative questionnaires reporting an average of about 50% of the price of the stove to the individual stove maker with a previous study reporting 44%[99]. Average monthly revenue was reported as 8,882 RWF ($11.81) per stove maker though this varied highly based on demand for the stoves. Still, even at the higher range of profit (11,322 RWF, $15.73 per month)[98], a stove maker would still be making less than three times Rwanda's current GDP per capita of $638[110], resulting in cooperative members reporting that they did not see working in a stove cooperative as full time work. While many cooperatives are not currently operating at full capacity, additional revenue could be achieved with higher demand but is not likely to provide enough income to meet a Rwandan household's financial needs.

Though, local capacity building should be viewed more broadly than profits to individuals. While it is unknown how many cooperative members have been trained to make the local stoves, it is likely that hundreds to thousands of Rwandans have acquired additional skills in the production of stoves. Moreover with thousands of trained stove makers being located geographically close to the users, benefits related to long term maintenance of the stove may be realized.

Economic Sustainability

Based on DALY calculations from the social sustainability assessment and the cost estimates for capital and on-going fuel costs, the cost effectiveness in dollars per DALY was calculated, again using the HAPIT model[111]. Figure 3 shows the cost per averted DALY for the imported and locally made stoves. Additionally the figure shows the two scenarios of entirely wood collectors and entirely wood purchasers. In the case of the wood collectors, where there is no annual cost for fuel, the locally made stove provides an averted DALY for approximately half the cost of the imported stove. However, when the stove user has to purchase fuel over the four year lifetime of the stove, a DALY is approximately four times higher due to the higher efficiency of the imported stove.

Comparing Rwanda's GDP per capita of $638[110] to the WHO CHOICE's definition of cost effective (< GDP/capita) and very cost effective (<3x GDP/capita), both stoves fall within the cost effective designation for wood collectors, with the locally made stove designated as very cost effective. In the case of the wood purchasers, neither meet the criteria for cost effectiveness.

Figure 3. Cost per averted DALY for the imported and locally made stove considering households which collect and purchase fuelwood.

Implications

Both stoves have important attributes in contributing to the sustainability of an improved cookstove program. While neither stove can be said to be of superior sustainability, lessons can be learned from both technologies to move towards a more sustainable stove overall. Environmentally, stoves performed well on different impact metrics but with the primary environmental metric, global warming, being estimated at about half for the imported stove over the locally made stove. This outcome can mostly be attributed to the large contribution of the use phase over the raw material, production and transportation phases. Generally, efficiency of the stove is the primary driver in environmental impacts. From a social sustainability perspective, the imported stove offers a key benefit around local capacity building but would need to be expanded in order to fully realize this benefit. Also, while the imported stove performed better in improving health, neither stove provided sufficient health benefit to meet WHO standards. In the context of economic sustainability, wood procurement method was relevant in the overall cost effectiveness of either technology. Specifically in households where wood is purchased, cost-effectiveness will not be achieved while wood collecting households, with no on-going fuelwood cost, will likely achieve cost-effectiveness.

Overall, components from both stove technologies may be integrated to develop a more holistic cookstove based on all sustainability principles. A possible compromise may include local assembly with parts manufactured abroad and shipped in. However, the primary challenge will be designing a cookstove which can be highly efficient to reduce global warming emissions and drastically reduces emissions to meet social metrics while also maintaining a low enough cost to be considered cost effective.

Study 4 – Supporting Information

Environmental Sustainability Calculations – Life Cycle Analysis

EcoZoom Dura Stove

The EcoZoom Dura stove was modeled based on materials and process descriptions provided by EcoZoom. Most processes were modeled by the ecoinvent database[103]. As many processes are not modeled specifically for conditions in China, the "global" dataset or "rest-of-the-world" datasets were utilized as an appropriate assumption for raw material procurement and production in China.

Raw Materials and Production

The EcoZoom Dura stove primarily consists of steel, cast iron and ceramics. Miscellaneous bolts and other smaller components were considered negligible and thus not considered in this analysis. As both the raw material procurement and production phases are conducted in China, the EcoZoom analysis includes significant transportation inputs from shipping and land transport of the stoves from China to Rwanda.

<u>Low-Alloyed Steel</u>

Several components of the stove including the stove body, doorway, stick support and spring inserts are primarily made from low-alloyed steel. It was assumed that crude steel in China is largely produced in blast furnaces and basic oxygen furnaces instead of electric arc furnaces[112]. In total, the estimated weight of the low-alloyed steel is 1.33 kg. Environmental impacts per kg of low-alloyed steel are shown in Table 1.

Cold-rolling

Many of the steel components including the stove body and doorway are processed through cold rolling. An estimated 1.06 kg of steel in the stove is cold rolled. Environmental impacts per kg are shown in Table 1.

Galvanized

The stove body is additionally galvanized which adds the zinc coating process to the life cycle analysis. An estimated 0.062 square meters of steel is galvanized per stove. Environmental impacts per square meter of steel are shown in Table 1.

Stainless Steel

Several steel components are made from 201 stainless steel. Unfortunately 201 stainless steel is not modeled in the ecoinvent database and thus 18/8 stainless steel was used to model the stainless steel components of the stove. Again, is was assumed that steel is produced in blast furnaces and basic oxygen furnaces. An estimated 1.3 kg of stainless steel is used per stove. Environmental impacts per kg are shown in Table 1.

Cast Iron

The stove top of the EcoZoom stove is made of cast iron. The total weight of the top is 2.67 kg. Environmental impacts per kg of cast iron are shown in Table 1.

Ceramics

The primary insulation material inside the stove is ceramics made from organic materials. This process was modeled within the ecoinvent database as the production of refractory stove bricks. An estimated 3.9 kg of ceramic material is used per stove and its environmental impacts per kg of ceramic are shown in Table 1.

Impact category	Low-alloyed Steel (per kg)	Cold-rolling (per kg)	Galvanized (per m^2)	Stainless Steel (per kg)	Cast Iron (per kg)	Ceramics (per kg)
Ozone Depletion (kg CFC^{-11} eq)	1.36E-07	3.40E-08	6.70E-07	3.17E-07	1.16E-07	9.34E-08
Global warming (kg CO_2 eq)	2.58	0.42	5.32	4.65	2.01	0.73
Smog (kg O_3 eq)	0.142	0.025	0.492	0.306	0.105	0.075
Acidification (kg SO_2 eq)	1.15E-02	2.31E-03	3.02E-01	2.83E-02	9.05E-03	4.34E-03
Eutrophication (kg N eq)	1.82E-02	1.30E-03	4.64E-02	1.65E-02	5.26E-03	1.21E-03
Ecotoxicity (CTUe)	1.4165E-06	2.43814E-07	4.33336E-07	2.72508E-06	2.78007E-06	1.82493E-08
Fossil fuel depletion (MJ surplus)	2.89055E-06	7.73678E-08	3.04387E-05	2.49936E-06	2.75271E-06	6.82773E-08
Carcinogenics (CTUh)	4.77E-03	4.74E-04	1.75E-02	1.37E-02	2.75E-03	5.31E-04
Non carcinogenics (CTUh)	86.9	10.9	156.2	98.2	47.9	2.4
Respiratory Effects (kg PM2.5 eq)	1.18	0.37	5.68	3.45	1.10	1.44

Table 1. Environmental impacts of raw materials for the imported stove.

Transport

To reach Rwanda, the finished EcoZoom Dura travels from a shipping port in China to a shipping port in Tanzania. Road transport is then required from Tanzania to Rwanda. Transport from the manufacturing facility to the shipping port was neglected as the distance is relatively short. Additionally, the transport is only calculated to the capital of Rwanda, and not to each individual household. The assumption of neglecting transport to each household is made for the both the EcoZoom and Canarumwe stoves.

<u>Sea Transport</u>

Stoves are transported from the port in Ningbo, China to Dar Es Salaam, Tanzania on the Eastern Coast of Africa. Transport was modeled in a transoceanic freight ship with an assumed travel distance of each stove of 11479 km. Environmental impacts per ton kilometer (tkm) are shown in Table 2.

Land Transport

After stoves arrive in Dar Es Salaam they are transported by road to Kigali, Rwanda. Transport was modeled using a 20 – 28 ton fleet average for freight container trucks. The assumed travel distance for one stove is 1500 km. Environmental impacts per tkm are shown in Table 2.

Impact category	Sea Transport (per tkm)	Road Transport (tkm)
Ozone Depletion (kg CFC^{-11} eq)	1.61E-09	4.17E-08
Global warming (kg CO_2 eq)	1.07E-02	1.94E-01
Smog (kg O_3 eq)	3.55E-03	4.07E-02
Acidification (kg SO_2 eq)	2.38E-04	1.35E-03
Eutrophication (kg N eq)	2.43E-05	2.47E-04
Ecotoxicity (CTUe)	3.64E-10	1.06E-08
Fossil fuel depletion (MJ surplus)	8.80E-10	2.92E-08
Carcinogenics (CTUh)	1.48E-05	9.93E-05
Non carcinogenics (CTUh)	0.0182	0.6439
Respiratory Effects (kg PM2.5 eq)	0.0201	0.4206

Table 2. Environmental impacts for transportation of the imported stove.

Use Phase

Usage and emissions data for both stoves were modeled based on reported reductions from a three stone fire[113]. Three stone fire usage in Rwanda is assumed to be 1888 kg per household per year[19]. While some “improved” stove usage was reported within this wood quantity number, most Rwandan families cook primarily on a three stone fire and “improved” stove usage was from very basic stoves and thus it was assumed a value of 1888 kg of wood were used per family per year under a three stone fire scenario. Households were assumed to be using primarily Eucalyptus with a heat content of 18.0 MJ/kg[114]. To calculate EcoZoom wood usage, a 65.8% reduction in wood usage was assumed based on a previous study[69], resulting in an assumption of 646 kg per family per year. Additionally, emissions from the EcoZoom dura compared to a three stone fire were assumed to be reduced by 50.6% based on particulate matter ($PM_{2.5}$) measured in a laboratory study[97]. Finally, emissions were taken over the assumed four year lifetime of the stove. Environmental impacts per kg of wood used are shown in Table 3.

Impact category	EcoZoom Use (per kg fuelwood)
Ozone Depletion (kg CFC^{-11} eq)	0
Global warming (kg CO_2 eq)	0.99
Smog (kg O_3 eq)	0.027
Acidification (kg SO_2 eq)	8.29E-04
Eutrophication (kg N eq)	5.40E-05
Ecotoxicity (CTUe)	0
Fossil fuel depletion (MJ surplus)	0
Carcinogenics (CTUh)	4.42E-05
Non carcinogenics (CTUh)	0
Respiratory Effects (kg PM2.5 eq)	0

Table 3. Environmental impacts from use phase of the imported stove.

End-of-Life

Environmental impacts related to the end-of-life phase were not analyzed. Products in a Rwandan household are often repurposed after they no longer serve their original purpose or discarded. Any waste generation is assumed to be negligible.

Canarumwe Stove

The Canarumwe stove was modeled based on questionnaires from six stove cooperatives, the producer's manual, existing emissions and fuelwood data.

Raw Materials and Transport

The Canarumwe stove consists primarily of three ingredients: clay, sand and water. One cooperative reported adding soil occasionally to their mixture but this was not considered as it was only one cooperative and was not typical. Wood is also required to fire stoves in a kiln.

<u>Clay</u>

Clay is the primary ingredient in the production of the Canarumwe stove. Clay quality is an important factor as it affects the strength and thus overall lifetime of the stove. All cooperatives collect clay through manual labor while three reported transporting clay by foot with the other three transporting clay less than 10 km by truck. An average of 9.3 kg (5.0 – 13.2 kg) of clay was assumed to produce a single stove based on questionnaire responses with the assumption of using a 3.5 – 20 ton diesel powered truck for 5 km. No environmental impact was estimated from the clay besides material transport as only manual labor was used for clay extraction.

Sand

Sand is added to the clay based on the composition of the raw clay material. The producer's manual suggests no greater than 30% sand to 70% clay ratio. Five of the six cooperatives reported collecting sand only by foot and thus transportation will be neglected for procurement of sand. Questionnaires reported an average of 1.7 kg (0.3 – 2.7 kg) of sand which was assumed to produce a single stove. No environmental impact was estimated from the sand as only manual labor was used for sand procurement.

Water

Water is added to create a workable clay structure while creating a consistent mixture. Water is typically kneaded into the stoves by manual labor. All cooperatives reported collection of water by foot with an average of 3.7 liters (1.2 – 11.1 liters) of water used per stove produced. Water is primarily collected from natural springs and surface water sources. No environmental impact was estimated from the water as it was collected from surface water sources which don't require infrastructure for transporting or processing.

Wood

Wood is the only fuel source used during the stove firing process. Most cooperatives reported buying fuelwood with one cooperative collecting all fuelwood. Additionally three cooperatives transported fuelwood by foot while the other three hire a truck to transport the fuelwood less than 10 km. An average of 3.5 kg (2.7 – 5.3 kg) of wood was reported which was assumed to produce a single stove with an additional assumption of wood transport in a 3.5 – 20 ton diesel powered truck for 5 km. No environmental impact was estimated from wood harvesting as most wood come from untended or minimally managed tree plantations which use only manual labor in procurement of the wood.

Production

After raw materials have been procured and transported to the stove cooperative, they are prepared, processed and finally fired to manufacture a complete Canarumwe stove.

<u>Clay Preparation</u>

Several methods are used in clay preparation depending on the quality and composition of clay used by each cooperative. Some cooperative will dry the clay and then grind, crush and sieve the clay before adding water in order to produce a smooth clay. More commonly in the cooperative interviews in this study was soaking the clay/sand mixture in water then kneading and pounding out the clay. All cooperatives reported that the clay was only ready when it produced a scratchy texture. Regardless of the method, no environmental impact was estimated from the clay preparation process as only manual labor was used.

<u>Stove Shaping</u>

The prepared clay is shaped into the stove through use of a standardized mold. The clay is inserted into the base of the mold where a paddle is then rotated to shape the clay. The stove is then removed from the mold to smoothen and repair any cracks. Finally the fuel opening is cut away from the door and clay notches which where a cooking pot will sit are added. The stove is left to dry for a few days before the firing process. No environmental impact was estimated from the stove shaping procedure as only manual labor was used.

Firing

The shaped stove is fired to harden the clay into a finished ceramic. Most cooperatives reported firing stoves through the use of a wood fired kiln. As most cooperatives were previously or concurrently producing pottery products, many kilns already existed and thus the original kiln infrastructure was excluded from the environmental impacts of this life cycle analysis. After stoves are placed in the kilns, the kiln is covered with mud. Fuelwood is used to fire the stoves for approximately eight hours. Cooperatives identify the mud changing to a red color and the stoves closer to the top turning brown as indicators of the finished firing process. Environmental impacts from the firing process were estimated in TRACI using the heat content of Eucalyptus (18.0 MJ/kg)[114] and emission values for stoves used in developing communities[113]. These values are summarized in Table 4.

Impact category	per kg of Eucalyptus
Ozone Depletion (kg CFC^{-11} eq)	0
Global warming (kg CO_2 eq)	3.0
Smog (kg O_3 eq)	0.055
Acidification (kg SO_2 eq)	1.868E-03
Eutrophication (kg N eq)	1.21E-04
Ecotoxicity (CTUe)	0
Fossil fuel depletion (MJ surplus)	0
Carcinogenics (CTUh)	9.83721E-05
Non carcinogenics (CTUh)	0
Respiratory Effects (kg PM2.5 eq)	0

Table 4. Environmental impacts from kiln emissions from local stove.

Use Phase

The use phase of the Canarumwe stove was calculated similarly to the EcoZoom stove. Fuelwood reduction from a three stone fire was estimated as 50% based on a previous field study[101] and an emission reduction of 26.2% based on a laboratory study[97].

End-of-Life

The Canarumwe end-of-life phase was also neglected similarly as the EcoZoom stove.

Social and Economic Sustainability Calculations

Household Air Pollution Intervention Tool (HAPIT)

Personal exposure had to be estimated for the locally made stove because of unavailable data. Emissions data from a laboratory based study[97] and existing personal exposure data from a recent field study[106]** was used to extrapolate the personal exposure of the locally made stove. The $PM_{2.5}$ emissions of a three stone fire and the StoveTec GreenFire, an earlier model of the EcoZoom stove, were plotted with the field based personal exposure data from a randomized control trial. The control group personal exposure measurement was used as a proxy for the three stone fire while the intervention group personal exposure measurement was used for the EcoZoom. Both measurements assume exclusive use of a three stone fire or the EcoZoom which is likely not the case but is a conservative estimate. A linear regression was then performed and the emissions measurement for the Upesi stove, an earlier model of the Canarumwe stove, was fit to the model to achieve a personal exposure measurement. It should be noted that the emissions data included three tests; a cold start, hot start and simmer test. Only the simmer test was used for the regression as the other two tests resulted in $PM_{2.5}$ emissions higher than the three stone fire which could not be modeled within HAPIT. Figure 1 and Table 5 below show the results of this analysis.

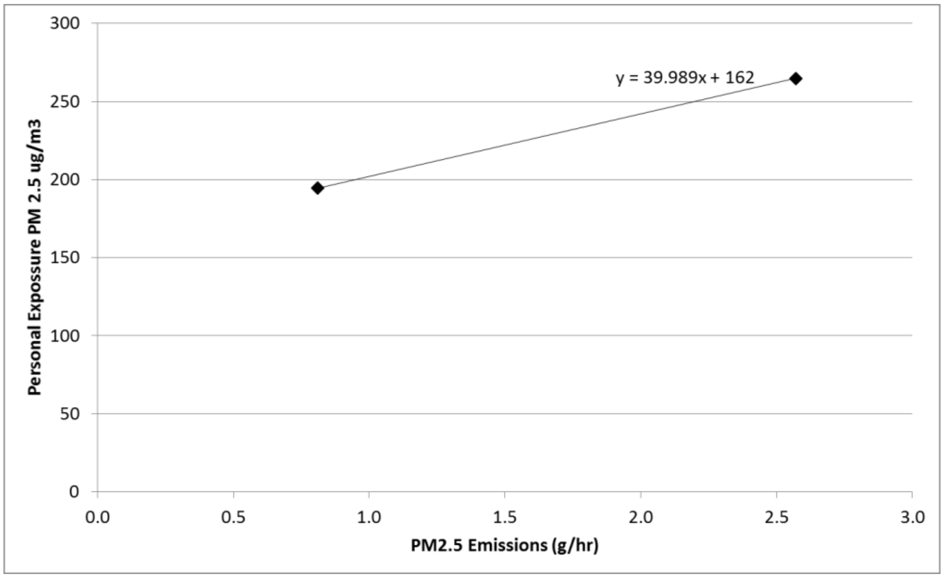

Figure 2. Extrapolation calculation to convert emissions to exposure values.

Stove	Emission (g/hr)	Personal Exposure (ug/m^3)
Three Stone Fire	2.57	264.8
Imported	0.81	194.4
Local	1.88	237.2*

*Extrapolated value

Table 1. Extrapolated personal exposure values

Based on assumptions outlined in the main journal article, inputs to the HAPIT model are summarized in Table 6 and the relevant outputs generated from the HAPIT model are summarized in Table 7.

Inputs							
Pre-intervention exposure	264.8	ug/m3	Average bundle weight	28.3	kg		**kg/stove/year**
Counterfactual	10	ug/m3	Average price per bundle	1629	RWF	Imported	646
Country	Rwanda		Rwanda GDP per capita	$638.00		Local	944
Wood Procurement	**Stove**	**Post PM2.5**	**Targeted Households**	**Frac Using**	**Lifetime (years)**	**Capital $**	**$/year**
Collection	Imported	194.4	25,000	1.0	4.0	**	$0.00
Collection	Local	237.2	25,000	1.0	4.0	$3.00	$0.00
Purchasing	Imported	194.4	25,000	1.0	4.0	**	$51.62
Purchasing	Local	237.2	25,000	1.0	4.0	$3.00	$75.47

**The price of the EcoZoom stove is proprietary

Table 6. HAPIT model inputs.

Output						
Stove	**ADALYs <5s**	**ADALYS adults**	**Averted Deaths <5s**	**Averted Deaths adults**	**$/DALYs (Collectors)**	**$/DALYs (Purchasers)**
Imported	540.0	193.0	6.3	4.2	$716.00	$11,300.00
Local	170.0	69.3	1.9	1.4	$313.00	$47,600.00

Table 7. HAPIT model outputs.

Conclusion

Sustainability is a term which can be difficult to define and can take on various meanings depending on the context. The aim of this research was to look at sustainability from several different lenses in the international development setting. Specifically a large scale public health program was examined from the following perspectives:

- Adoption – Is the program accepted by the target population and why? The first fundamental facet of a sustainable program is actual use of technologies. Without meaningful adoption rates and positive behaviour change, a program will not last beyond the short term and thus long-term sustainability will not be realized.
- Cost Benefit – Does the program provide enough benefits to outweigh its cost? While a program may aim to provide a specific benefit to the target population, it can only be sustainable if the inputs into the program result in substantial impact. Scarce resources spent on programs with little benefit will not provide overall sustainability to the international development sector.
- Technology Selection – Do locally made products or imported products provide greater benefits from an environmental, social and economic perspective? Products should be measured based on a holistic approach whereby all metrics of sustainability are considered. Imported and locally made products have value in differing sustainability metrics and must be considered as a whole during product selection.

Sustainability of the *Tubeho Neza* program was assessed based on the above perspectives through the four research studies conducted in this research.

Adoption

The pilot program reported high levels of uptake and continued use of water filters and improved cookstoves through a rigorous five month follow up study with monitored results 16 months after the intervention. In the case of the filter, adoption was measured around 90% for the five months of the study. However, while adoption of the filter was high, the recommended water consumption of 2 liters per person per day was not reached in most cases, suggesting that households may be drinking untreated water at times. Given that even occasional consumption of untreated water can greatly reduce the potential health benefits from water quality interventions[25,26], further activities to promote exclusively drinking clean water were suggested in a scaled up program model. Adoption of the stove was also around 90%. Non-health benefits such as a cleaner appearance and cooking environment were more highly valued than health or environmental impacts. Exclusive use, also known as "stove stacking," was also an issue with the intervention stove with 28.5% of households reporting continuing to use their old stove while using the EcoZoom stove. Similarly to the water filter, to realize the potential health benefits of improved stoves, exclusive use will need to be further promoted[27–29].

Based on results from the pilot study, the intervention was scaled 50 fold to a regional program. A study conducted through the first year following distribution of the products again found high levels of initial adoption of the water filters and cookstoves, around 90%. Filtered water quantity increased from the pilot study of 1.27 liters per person per day to 1.63 liters per person per day. The increase may be attributable to increased emphasis in the behavior change program including added messaging about the importance of hydration and specific activities on the household poster which outline how much water should be treated each day in order for the whole family to drink two liters per person day. Overall reported stove adoption was also comparable to the pilot, though improvements were made in stove stacking behavior. Reported use of other stoves reduced by over 20% to about half of households reporting still using other stoves, with percentage of cooking events on the EcoZoom stove in the household increasing by at least 15%. While these results are promising in moving towards exclusive adoption of improved stoves, they will not be sufficient in meeting the World Health Organization's guidelines for indoor air pollution[74] which would involve switching to much cleaner fuels and stoves in order to meet recommendations.

From an adoption perspective, the *Tubeho Neza* program can be characterized as sustainable based on the high level of adoption measured from the pilot to the full scale. Overall the *Tubeho Neza* program was able to demonstrate a privately financed, public health intervention can achieve high levels of initial adoption and usage of household level water filter and improved cookstoves at large scale. However, long term program sustainability should be closely monitored based on the volatility of the carbon market which is one of the primary funding mechanisms of the *Tubeho Neza* program. Carbon credit prices can vary greatly between countries, programs and type of carbon markets. Prices can range anywhere from $130 to less than $1 depending on a variety of programmatic and buyer priorities[87]. Additionally after the Paris climate talks it is unclear how carbon markets will change and how it could affect a developing communities program such as *Tubeho Neza.* In order for true long term sustainability to be realized, the financing strategy may need to change or include more diverse funding streams.

Cost Benefit

The cost benefit analysis found the *Tubeho Neza* large scale intervention to be highly beneficial with an expected 7.2 benefit to cost ratio. An estimated 1.18 million tons of total fuelwood will be saved over the ten year lifetime of the program, equating to approximately 11.6 tons per household. Fuelwood savings from the improved cookstove alone provide benefits almost six time the cost of the program with the fuelwood savings from the water filter being the primary driver of water filter benefits. Environmental impacts accounted for only 12% of the total CBR, however reduced deforestation will help Rwanda to make up for its large deficit in sustainable fuelwood resources and save over 1.4 million tCO_2 emissions. Additionally, while time savings provided less than 10% of the overall benefits, households who collect fuelwood may save approximately 48 days per year collecting fuelwood while households who previously boiled may save approximately 23 days not performing the task of boiling water for drinking.

Based on a ten year projection, the *Tubeho Neza* program, can be considered sustainable from a cost-benefit perspective based on the benefits significantly outweighing the cost of the program. The *Tubeho Neza* program is an example of a how large scale public health program can potentially produce a positive benefit to cost relationship in an international development setting.

Technology Selection

Imported and locally made stoves both contribute substantially, but by very different means, to sustainability of a program. From an environmental perspective, both stoves can provide benefits, but most significantly global greenhouse gas emission reduction will be more significant with an imported stove mostly due to the use phase of the stove versus the production and transportation stage. Examining social metrics, the imported stove will perform better based on health and scalability metrics while the imported stove will provide substantial benefits related to local capacity building. Considering cost effectiveness to evaluate economic sustainability, the imported stove will outperform the locally made stove in the context of wood collectors while the locally made stove will perform more highly with people who purchase wood, due to the high capital cost of the imported stove. Both are considered cost effective in the wood collecting scenario while neither are cost effective in the wood purchasing scenario.

Overall neither the imported or locally made stove could be deemed more or less sustainable. However, a hybrid approach may be possible which could include specific manufacturing of parts to increase local capacity while still producing highly efficient stoves in an importation model.

Future Work

Further development of all studies outlined here could provide additional contributions to the literature. The *Tubeho Neza* program itself should be continually monitored through the lifetime of the program. Given the analysis presented here represents short to medium-term adoption, a similar study at three to five year will give a better understanding of long term adoption. Specific studies related to behaviors which change over time and any trends in the long term which could affect adoption rates would greatly contribute to the literature. Additional research is necessary on some of the fundamental design criteria such as the free distribution and financing methods of the *Tubeho Neza* program as these are highly debated topics which require further evidence to inform future intervention design criteria.

A global cost benefit analysis of a variety of public health interventions would be an important contribution to the overall international development literature. While guidelines exist for cost effective interventions and many studies report both cost effective and cost benefit ratios, no study could be found which provides potential cost benefit ratios across sectors such as water, energy, malaria prevention and vaccination. Such a document could help implementers decide how to allocate scarce resources in the implementation of public health programs.

Lastly, to build on the mostly literature based review presented in this document, a field study based comparison of an imported and locally made stove are an important next step in the topic of where stove procurement should occur. Important advances in the development of improved cookstoves is progressing rapidly with manufacturing engineers working closely with social scientists and economists to design a cookstove which can contribute to all aspects of sustainability. A study which characterizes actual on-the-ground differences between imported and locally made products will provide important insight into key design decisions.

Engineering for Developing Communities

The research outlined here is highly relevant to the Mortenson Center in Engineering for Developing Communities (MCEDC) program. All studies are based in a developing country and have the potential to contribute to the larger international development literature. Specifically, reporting of program design while measuring program outcomes, provides an additional data point to the growing literature on water filtration and cookstove adoption. Similarly, the cost benefit study provides evidence for the further implementation of public health programs at a large scale. Finally, the study comparing locally made and imported cookstoves provides an analysis of a highly debated but very important topic in appropriate technology selection and suggests a possible hybrid approach.

The MCEDC curriculum itself has enabled this research through a diverse course selection of both technical and socially minded classes as well as a focus on cross-sector collaborative learning. This research in particular involved working with several researchers outside of the engineering discipline including public health experts, economists, and social scientists. Generally this approach allows the creation of global engineers who can work across multiple disciplines including economics, global health, governance and social entrepreneurship.

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