The Effect of Solar Ovens on Fuel Use, Emissions, and Health: Results from a Randomized Controlled Trial

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Abstract

Inefficient cookstoves contribute to deforestation and global climate change, require substantial time (usually of women and girls) or money for fuel, and lead to over 1.5 million deaths a year from smoke exposure. We ran a randomized controlled trial in rural Senegal to measure how solar ovens affect wood usage, time spent collecting wood, carbon monoxide exposure, and respiratory illness symptoms. In the sixth month of owning the stove, women in the treatment group used their oven about 19% of days. However, because 80% of our respondents typically cook for more people than the capacity of the solar oven, even cooks using the solar oven always had a fire going at the same time. On average, treatment households did not have statistically significantly lower fuel consumption, time spent collecting fuel, or time spent next to the cook fire. There is no evidence solar ovens reduce exposure to carbon monoxide or self-reported respiratory symptoms such as coughs and sore throats.

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There were, however, provocative differences by household size. For respondents cooking for 7-12 persons, the introduction of a solar oven reduced daily fuel consumption about 14% ($P < .01$). Also, a few results suggest that effects may have been larger in multi-household compounds with more than one solar oven. Finally, this impact evaluation was a policy success because its results halted the proposed nationwide rollout of the solar oven.

Over 3 billion people worldwide burn wood and other biomass for cooking (Mehta, *et al.* 2006). Most use traditional stoves such as three-stone fires that are very inefficient at transforming wood into heat that cooks food. Traditional stoves also expose cooks and children who stay near them to high levels of dangerous emissions, particularly if the stove is indoors. Emissions from burning biomass cause approximately 1.6 million premature deaths every year (WHO, 2007b). In rural areas women and girls spend many hours a week gathering fuel wood – time that is then not available for school or earning money. Burning biomass fuels also contributes to deforestation and to global climate change. Improved stoves have the potential to reduce all of these problems.

Despite generations of efforts, however, improved biomass cook stoves have not yet reached most of the world's poor (Household Energy Network, 2008). Few improved stoves programs have included rigorous evaluation of the impacts and of barriers to achieving widespread adoption. Rigorous evaluations are crucial to determine if "improved" cookstoves actually reduce fuel use, greenhouse gas emissions, and harmful emissions. Further, scientific evaluations are also crucial to understand the cause of slow technology adoption and can provide needed evidence to determine the appropriate response by stove designers, stove distributors, and/or policy-makers.

Authors of the few existing rigorous evaluations of the impacts of improved stoves cite the wide agreement in the scientific community that additional rigorous evaluations are needed to accurately evaluate the impacts of improved stoves, particularly on health (Bruce, *et al*., 2006; Smith, *et al.* 2000; Duflo, *et al.* 2008). For example, adoption may be slow because consumers fear the new stoves break often (as found in Duflo, *et al.*, 2007) or do not meet consumers' needs. If stoves do not lead to savings, the appropriate policy response is promoting additional research into stove design and market needs. In contrast, a rigorous evaluation showing durable stoves leading to fuel savings can encourage consumers to adopt the new stove.

New cookstoves might not be adopted because of barriers within the household such as lack of information or lack of credit. Evidence about these barriers can help donors, policy-makers, and NGOs promoting improved stoves design better marketing and creative contracts. For example, if credit constraints are important barriers, stove distributors might partner with microfinance institutions.

Finally, adoption might also be slow due to externalities that are not priced, such as the release of greenhouse gases. Importantly, improved stoves that reduce greenhouse gases may be eligible for "carbon credits." Rigorous evaluations are crucial to determine the reduction in emissions and corresponding eligibility for credits.

We perform a ***randomized controlled trial*** by phasing in the distribution of solar ovens in rural Senegal to interested women over six months. We examine how solar ovens affect fuel use, the time and money spent on fuel, exposure to carbon monoxide and self-reported health. While for smaller household sizes and households with more than one solar oven in the compound there are some small effects, overall the solar oven had few effects on the impacts we measure. The households we study suffer the ill-effects of traditional stoves.

Thus, a larger improved stove more suitable with the larger household sizes might be widely adopted in northern Senegal and similar regions.

Literature review

Over 80% of Sub-Saharan Africans burn biomass for their main energy source (WHO 2007b). In this section we briefly review the evidence linking inefficient biomass stoves to health problems, poverty, and the destruction of the natural environment.

Health effects are the most tragic consequences of traditional cookstoves. The WHO estimates that indoor air pollution is responsible for 3.6% of the global burden of disease (WHO 2010). Indoor air pollution is associated with respiratory infections such as pneumonia, lung cancer, bronchitis and emphysema, weakened immune system, and reduced lung function, and chronic obstructive pulmonary disease. There is also growing evidence that indoor air pollution may cause low birth weight, cataracts, lung cancer, otitis media (ear infections), and tuberculosis (Clark,*et al.* 2007).

The most convincing evidence linking emissions from cookstoves and poor health comes from the RESPIRE study in rural Guatemala. The RESPIRE study found that moving from a traditional smoky indoor cookstove to a large built-in stove with a chimney reduced both exposure to carbon monoxide and women's self-reported health symptoms. Importantly, the improved stoves also reduced the incidence of childhood pneumonia (Smith-Silvertsen, *et al* . 2004; Diaz, *et al.* 2007).

These results are consistent with the large literature linking improved cookstoves to reduced emissions in carefully controlled conditions (e.g., McCracken and Smith (1988), Ezzati and Kammen (2002), Ezzati, Saleh, and Kammen (2000), Ezzati, Mbinda, and Kammen (2000), Dasgupta *et al.* 2004a, Dasgupta *et al.* 2004b, Dherani *et al.* 2008, and Albalek *et al.* (2001)). A concern with this valuable literature is that results may not apply directly in field settings; for example, the measurements on stoves do not tell us directly about how cooks' exposure to emission will change, if some cooks use multiple stoves. The RESPIRE results are also consistent with the non-experimental literature correlating traditional cookstoves with poor health (for a summary see Bruce *et al.* 2000). This literature is also very valuable, but there remains concerns that the observed correlations between traditional cookstoves and poor health could be due to generally poor people having both traditional cookstoves and poor health due to their overall poverty.

In addition to health problems, traditional stoves can also lead to burdensome fuel costs. In rural Africa, gathering fuel takes many hours a week for the average household (Blackden and Wodon, 2006). In almost all cultures, women and girls have primary responsibility for gathering wood (*ibid.*), time that is then not available for school or earning money. There is suggestive evidence wood-gathering duties reduce education, at least in wood-poor regions (Bruce, *et al.*, 2006).

Environmental degradation is another serious consequence of inefficient cookstoves. Gathering firewood contributes to deforestation and desertification (United Nations Convention to Combat Desertification 2010). That deforestation, in turn, contributes to global climate change. Bailis, *et al.* 2005 estimate that under current trends, household energy use in Africa will produce a total of 6.7 billion tons of carbon by 2050.

The Intervention

Rural Senegal is subject to all of the ill-effects of traditional cookstoves: pneumonia and other respiratory infections closely linked to indoor air pollution are the leading cause of death (WHO (2007a); fuel collection takes many hours a week; Senegal is part of the sub-

Saharan Sahel region which suffers from desertification when trees are cut down (Reuters, 2007); and Senegal is also in one of the world's most vulnerable zones for climate change (United Nations Convention to Combat Desertification 2010).

Given the important role energy places in poverty, the Government of Senegal under President Abdoulaye Wade, has made renewable energy, particularly solar energy, a national priority (Associated Press, 2006). One indication of the governmental priority was the 2008 appointment within the Ministry of Energy of the first Minister for Biocarbons, Renewable Energy and Scientific Research–the first appointment of its kind in Africa (personal communication, Ministry of Energy officials, Dakar Senegal, June, 2010).

With these facts in mind, the NGO Solar Household Energy, Inc. (SHE) approached the NGO Tostan about deploying SHE's HotPot solar oven in Senegal.

SHE designed the HotPot in 2004, and the stove is manufactured in Mexico. SHE has distributed over 5000 HotPots in Latin America and Africa, including the 1000 for this pilot. SHE was interested in accelerating distribution of the Hotpot in Africa.

The HotPot uses a reflector to direct sunlight to a 5-liter black enameled steel pot that is within a larger tempered glass bowl with a lid. Heating occurs both from sunlight striking the black pot and from the greenhouse effect within the larger glass bowl. Effective cooking requires that the user angle the reflector to the sun, shifting it ever hour or so. Under a tropical sun the HotPot can cook rice in under an hour, a chicken in about two hours, and beans in four hours.

Tostan was an attractive distribution partner for SHE because Tostan had been active in Senegal since 1991. Tostan's signature initiative is a three-year Community Empowerment Program that combines literacy with village level organization to facilitate community-driven development projects. Tostan estimates that 80% of participants in its Community Empowerment Program are women or girls.

SHE's solar oven was attractive to Tostan as a means to improve health by reducing exposure to smoke (as well as retaining nutrients with the solar oven's slow cooking); fight poverty and empower women by lowering time spent gathering fuel and standing by a fire; and fight local and global environmental degradation (personal communication, 2008).

In 2007 SHE carried out a small pilot study in Méckhé, Senegal with 20 consumers. SHE staff reported all the women found the stove fit well with their needs.[2]

We worked with Tostan and SHE to design a larger-scale randomized controlled trial of the solar oven. Tostan considered this randomized trial a proving ground that would, if successful, lead to a national roll-out of solar ovens (personal communication, 2008).

Study Design

Tostan selected 20 villages in the Thiès region in northern Senegal for this pilot. Tostan wanted to work in areas with the potential for large reductions in fuel use and emissions, so selected villages that cooked primarily with wood. To ensure communities had experience with implementing development initiatives, Tostan also selected villages that had at least five years experience with Tostan and had graduated from their three-year Community

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2 SHE shared results from its unpublished pilot study with CEGA and Tostan during the project preparation phase, October 2007. Engineers at UC Berkeley verified that the Hotpot was well designed and would not break easily. In the field we learned that SHE had replaced the original aluminum stove reflector with a less sturdy cardboard reflector, mainly due to shipping and manufacturing costs associated with the aluminum reflector.

Empowerment Program.

SHE trained Tostan staff in the solar ovens. SHE and Tostan then carried out trainings and marketing demonstrations on how to cook with the Hotpot from Jan-March 2008.

Due to shipping constraints of the HotPot from Mexico to Senegal only half the target population could receive the stoves at one time. Thus the phased intervention fit well with the program needs.

Tostan scheduled 50 solar ovens for each of the 20 study villages. Within each village we randomly selected 25 households in each village to receive the solar oven at the time of the baseline survey (April 2008) and 25 to receive the oven when the second shipment arrived (October 2008). We invited all 50 households to participate in the three survey waves:

- Baseline: (April 2008)- Treatment households receive stove;
- One-month follow-up: (May 2008)- One month after Treatment receive stove;
- Six month follow-up: (October 2008)- 6 months after Treatment receive their stove; at the end of the day, the Control Households receive their stoves.

Tostan and SHE initially priced the solar oven at $23 (10,000 CFA), with a $5 (2000 CFA) down payment due on delivery.[3] However due to rising food prices and gas fuel shortages (Anne Look, 2009) in Senegal in 2009 Tostan cancelled the later time payments. Thus, the eventual price of the stove to consumers was $5.

Data collection

In April 2008, when the first shipment of stoves was ready for distribution, Tostan invited all the interested women to a village meeting. At this meeting we collected the baseline data while the project's solar cooking specialist trained the women on the solar oven. At the end of the day the team held a drawing in front of the project participants at the meeting to determine the 25 women who would receive a solar oven that day (treatments) and the 25 who would receive their oven when the second shipment arrived (controls). In some villages there were not initially 25 controls at the meeting and the village focal person added new participants after the baseline survey and lottery. Thus, we ended up with data on 790 women who took the baseline survey and participated in the lottery (not the 1000 we envisioned).

We ran a six-month follow-up in October 2008, the day Tostan distributed solar ovens to control households.

Both surveys covered demographics, fuel use, time collecting fuel, cooking practices- including those associated with the solar oven, self-reported respiratory symptoms for respondents and their children, and cooking-related symptoms for respondents.[4] For a subset of participating households we also measured carbon monoxide exposure for women cooking the lunch meal. At those households we also collected information on the cooking structure, time spent cooking lunch, and types of fuel.

We review our three most important sets of measures, the number of people a woman

[3] All exchange rate conversions are based on the official 2008 rate of 435.55 CFA per $1, which is the official exchange rate from the U.S. Treasury.

[4] A one month follow-up was also fielded. Because only 9% of households used the solar ovens on the average day during the first month, we had insufficient statistical power to analyze this data.

cooks for, stove usage, and the several impacts, in more detail.

People cooked for

In each survey we asked women the number of people she cooked for yesterday. We also measured adult equivalent of household membership, converting children into adult equivalents, in order to see if stove usage changes by age adjusted consumption patterns. Following Atkinson, *et al.* (1995), we use the OECD-modified equivalence scale (first proposed by Haagenars, *et al.* (1994). The OECD-modified equivalence scale assigns a value of 1 to the household head, of 0.5 to each additional adult member (18 years of age or more) and of 0.3 to each child (0-17 years of age). We calculate adult equivalent based on the list of all members currently residing at the household, instead of the number of people the woman reports cooking for. This is because we must have the age of all household members to calculate the OECD adult equivalence measure. The two measures (at baseline) are highly correlated (correlation is .82), and on average all household members are 2.3 persons higher than the number of people women report cooking for in the household.

Stove Utilization

Following Ruiz-Mercado *et al.* (2008), we used ibuttons as our stove usage monitors (SUMs). The ibutton is a computer micro-chip enclosed in a 16mm thick stainless steel case, which we installed on the lid of all solar ovens.[5]

We programmed the SUMs to take temperature readings every 30 minutes. The SUMs data indicate clear spikes when the solar oven is used; we use a reading of 110°F (43°C) or more to indicate usage. In our field tests, unused solar ovens left outdoors did not reach this temperature. Results were not sensitive to the precise threshold (see appendix 1).

We had SUMs in place during the first month of solar oven ownership (roughly April through May 2008) and during the sixth month (October through November, the month following our 6 month follow-up survey).

We also asked self-reported usage rates on the 6 month follow-up survey. Finally, we observed solar oven usage during household visits for the follow-up survey for the subsample where we measured carbon monoxide exposure.

Impacts

We collected data on use of wood and other fuels, cost of gathering and buying fuel, exposure to carbon monoxide, and self-reported health. When possible we combined both objective measures and self reports.

For fuel use, households reported how much wood, charcoal, gas, animal dung, and farm waste they used last week.

At baseline we also asked respondents to show us the amount of wood they used to cook lunch yesterday. Respondents took the wood from a large pile in the center of the village that the village point person supplied at each village meeting. We then weighed the bundle they set aside.

The follow-up survey took place at the respondents' homes. We asked respondents to set aside first the wood they used to cook lunch yesterday and then the wood they used to cook all the meals yesterday. Respondents set aside wood from their own stored supply. In the rare case the respondents did not have enough wood at their home at the time of the survey

[5] The ibutton is sold by Maxim. We appreciate advice from the RESPIRE team on the ibutton SUMs.

visit to represent a day's wood use, the team borrowed wood from the neighbor to complete the pile.

Households also reported how much time and money their households spent last week collecting and purchasing fuel. The follow-up survey has better measures for the subset of women who collect wood in bulk.

We measured exposure to carbon monoxide with Dräger Color Diffusion Tubes ("CO tubes"). Using the principles of gas diffusion and colorimetric reaction, the CO tubes measure the time-weighted average concentrations of carbon monoxide in parts per million per hour (ppm/hour).

We followed Dräger's recommendations and multiplied the reading by a factor they provided to adjust for local humidity levels. Further, we top-coded the 6 month CO data, bringing 5 of our 275 observations down to the 95th percentile (~32.19 ppm/hour).

With the help of Tostan's local village point person, we selected a subset of households randomly to receive the CO tube. However, enumerators were instructed to skip households who were cooking only with gas. Unfortunately, we did not retain the count of treatment and control women and compounds that were not given CO tubes because they cooked with gas.

To measure exposure to carbon monoxide while cooking lunch, enumerators attached the CO tube to each cook's attire in the morning in each of our 20 villages (between 8:30-10:00am) and collected them about 5 hours later (2:00-3:30 p.m.) after lunch. This timing implies we could not measure any reduction in smoke exposure among women who used the solar oven to pre-cook dinner.

At the baseline the initial distribution was later in the day, so 80% of women had lit their cookfire before we distributed CO tubes. In the sixth month follow-up measures we changed our survey techniques and were able to distribute 74% of the CO tubes before cooks had started the fire.

To measure whether solar ovens reduce smoke exposure, we followed Diaz, *et al.* (2007) and collected self-reported symptoms associated with traditional cookfires: eye discomfort, headache, irritated throat, and back pain during cooking.

We also asked women to self-report if in the last 7 days they had experienced any of the seven respiratory illness symptoms: fever; sore throat; runny or stuffy nose; cough; wheezing or trouble breathing; woke up with chest heaviness at night; and coughed up mucus. At each survey round we also asked them to report on 4 symptoms for each of their children: cough or difficulty breathing; cold and coughed up mucus; runny or stuffy nose; and wheezing. At the follow-up we also asked respondents to report all seven respiratory illness symptoms for their husbands.

Estimation

Because the treatment group has been randomly selected, we expect individuals assigned to the treatment and control groups to differ only through their exposure to the solar oven (plus sampling variation). Thus, we first examine the difference of means between the treatment and control groups. In some analyses we examine percent changes by dividing the difference in means by the control group mean.

When we have baseline data we also look at the double-difference, testing if the change in the mean outcome of treatments differs from that of controls.

We also analyze the core impacts of fuel use, wood collection time, and self reported health symptoms using OLS regressions controlling for baseline characteristics. The basic regression to test an outcome Y for woman i where the follow-up time is equal to 1 is:

$$Y_{vi1} = \alpha + \beta T_{vi} + \sum_k \gamma_k X_{vik0} + \sum_v \delta_v FE_v + \epsilon_{vi} \quad (1),$$

where the vector $\mathbf{X_{ik0}}$ is k control variables (measured at baseline, time = 0, and often including the baseline value of the outcome, Y_{vi0}), FE_v is a vector of village fixed effects. Because it is plausible the solar ovens had larger effects for smaller households, we interact the treatment effect with three indicators of household size: 6 or fewer people, 7-12, and 13 or more (T * small, T * medium, and T * large households).

The baseline household characteristics include the number of people women report cooking for and its square, wood use at lunch the day prior to the baseline, the amount of money spent weekly on wood, the amount of money spent weekly on gas, the amount of money spent weekly on charcoal, kilograms of rice, 3 indicators for women's salary category, and 3 indicators for the category of the husband's financial contribution to the household. Continuous measures were bottom- and top-coded to the 5^{th} and 95^{th} percentiles to reduce the influence of outliers. To maintain sample size, we include a dummy when observations on a control variable were missing, and impute that value at its mean[6].

It is possible the number of people a woman cooks for at the follow-up is affected by having a solar oven. Thus, we estimate equation 1, but replace the number of people a woman cooks for at the follow-up survey (and interactions with treatment) with the number she cooked for at baseline (and interactions with treatment).

To check robustness, we replace our three categories of the number cooked for with terciles of household adult equivalents: Small (1.5-4.2), Medium (4.3-7.3), and Large (7.4 and over). As with the categories of number cooked for, we interact these adult-equivalent size quartiles with the treatment dummy.

Carbon Monoxide Exposure: The dependent variable is carbon monoxide ppm/hour at the follow-up, and we include control variables from the baseline including village fixed effects, lunch kg. of wood used, number of people women reports cooking for, dummy variable equal to one if cooking area is semi- or fully enclosed, # of Respondent's 7 respiratory symptoms, # of 4 Respiratory symptoms for Average Child 5 years of age and under, minutes per day next to the cook fire, and # of Husband's 7 respiratory symptoms (Table 6).

In robustness checks we also add endogenous control variables: kilograms of wood used daily, the number of hours women report next to the fire, and dummy variables for: completely enclosed and has no windows; semi-enclosed with at least one window; a wall-less roof, and open air. We test whether poorly-ventilated kitchens had larger benefits from solar ovens by interacting treatment with a dummy equal to 1 for kitchens that are entirely or semi-enclosed. Due to smaller sample size, we analyze CO tube data for households of size 12 or fewer, as well as the three size categories. Finally, we condition on whether the fire was already lit when the carbon monoxide monitoring began.

[6] We imputed baseline measures of the number of people women cook for (and its square), wood use for lunch yesterday, the amount of money spent weekly on wood, the amount of money spent weekly on gas, the amount of money spent weekly on charcoal, kilograms of rice and of flour consumed per person per week. When used as control variables, we also imputed follow-up values of the number of people women report cooking for and its square and wood-use lunch yesterday.

Results

The study population

The Thiès region in Senegal is located in the Western area of the country and is predominantly Wolof speaking. The semi-desert region is part of the Western Sahel and, outside the rainy season from late June through August, is warm or hot and sunny.

The study area is rural and poor. Women in our sample have mean earnings of $1.86/day and their husbands give them another $3.28/day for household expenditures. Thus, the average household spends 43 cents per person per day.

In this region most women live in compounds, often in a circle of huts fenced off from the rest of the village. Compounds usually represent a polygamous household where multiple wives live together, though some involve brothers and their wives. Thirty-two percent of respondents in our sample live with one or more co-wife. Because some men have wives in multiple villages and households may be spread over other villages, on our surveys we defined "household size" as members of either the household and/or the same compound for whom the respondent cooks for regularly. For women who do live in compounds with other co-wives it is common for multiple wives to share cooking responsibilities, often rotating across meals or days of the week.

Wood is the most common fuel. Most households use a traditional three-stone wood fire, while at baseline fewer than 25% owned an improved stove. At the same time, most households also do some cooking on charcoal and/or gas stoves. The household's choice of stove depends on the meal, season, and size of household. At the six month follow-up CO survey respondents report cooking in a semi-enclosed kitchen (49%), an enclosed kitchen with no windows (21%); a kitchen with thatch roof but no walls (20%); or outdoors (10%).

Pipeline analysis

At baseline we surveyed 790 of the envisioned 1000 households in the combined control plus treatment groups (Table 1). To observe the effects of the program we limit our analysis to those households who took the baseline survey.

Twelve treatment households (>3%) returned their solar ovens and dropped out of the treatment group. Their most common explanation was an unexpected financial shock, most often a health problem which required all of the household's disposable income. Tostan redistributed these solar ovens to control homes leading to a small amount of leakage. Thirty-six control households (10%) dropped out of the program as well. Given the control households received their stoves six months after the treatment households it is possible that women in the control group dropped out more than the treatment group because they observed the solar oven was too small to cook for their household size.

Contrary to the intended study design, 33% (260) of our participant households lived in a compound with one or more study participant. 41% (236) of treatments had one or more treatment and/or controls living in the compound and 54% (176) of control households have one or more treatments and/or controls living in the compound. We use this unintended overlap to test whether solar ovens are more effective in compounds with multiple solar ovens.

Of the 790 who took the baseline survey 736 weighed wood. At the follow-up 744 households from the treatment and control groups took the baseline survey, of which 677 also weighed wood. Of those missing wood weighing, 67% on the baseline survey and 64% on the follow-up can be attributed to the household cooks primarily with gas. The 18 households at baseline and 24 households at the six month follow-up who do not weigh wood but do take the surveys and are not primarily gas users, can be attributed to measurement error.

We permit other women from the village (usually from the same compound) to complete the survey if the enrolled woman is not present. At the follow-up 48% of treatment and 45% of control households had a substitute respondent. This rate was high in part because the follow-up occurred during fish smelting season in two of our villages, when many people were absent. In addition, treatment respondents that had already received their solar oven had less incentive to be present in the village to take the follow-up survey than the control group, who were waiting for their HotPot.

Household size for our sample from both survey waves is on average 12 persons, of which 53% are female. The population is young, with 60% of household members 24 and under. Education levels are low, with 94% of those over age 50 reporting zero or missing education. For secondary school age youth education levels are improving though still remain way below the global average as 48% of youth 13-18 report zero or missing education.

Randomization tests

We ran a probit equation with the baseline variables listed in Tables 2, 3 4, including education, income, household size, time spent gathering fuel, kilograms of wood used, self-reported health, and so forth. The results were reassuring in that they collectively did not statistically significantly predict treatment (result in appendix 2).

For example, mean income per day (including both women and their husband's joint income) for controls is $5.10 which is statistically and substantively the same as for treatments: $5.12. Household membership is 54% female for controls and 54% for treatments (Table 2). Cooking time per day is 4 hours 53 minutes for controls and 4 hours 57 minutes for treatments. None of these differences approach statistical significance.

An important exception to balance between groups is that control women report cooking for a mean for 12.7 persons and treatment of 13.8 (difference $P < .05$). Because almost all other measures are statistically indistinguishable, we suspect this gap is due to sampling variation. At the same time, we control for baseline differences in the number of people a woman cooks for in our regression analyses below.

Summary statistics

Number of People Women Cook For

The median number of people women report cooking for yesterday (or, if they did not cook yesterday, then usually) on the baseline survey is 12. The majority of our sample, about 80%, consists of households larger than 6 persons (the size the HotPot solar oven was designed for).

Given the large household size, from the OECD adult age equivalent scales and the weighting that adults other than the household head count 1/2 and children count 1/3, the adult equivalent number of people a woman cooks for at baseline has a mean (median) of 6.25 (5.7). The mean and median remain substantially above the HotPot's capacity of 3.5 adult equivalents (assuming 6 adults).

Baseline and trends for controls

Households in our sample use a variety of fuels and gather wood they cook with in multiple ways.

In our baseline, 88% of households cook with wood. Households average 6.82 kg. (~15 pounds) of wood to cook the lunch meal. At the same time, 74% of households use gas-mainly to reheat meals or cook breakfast- and 21% also use charcoal, most often for tea. We learn that the majority of households are multi-stove users and multi-fuel users, consistent with utility maximization theory. At the baseline of the total households surveyed 88% of households respond they utilize wood, 50% use farm waste, 8% use animal dung, 21% use charcoal, and 74% use gas to cook with.

Control households spent 6 times more on wood and nearly 2.5 more on charcoal at the April baseline survey (end of the dry season) than at the follow-up (October, following the rainy season). It is likely purchases were high at baseline because wood was scarcer and thus harder to gather. Consistent with that hypothesis, unit costs (spending on wood divided by kilograms of wood, a proxy for price) were 75% higher for wood and about 50% higher for charcoal during the dry-season baseline than at the follow-up. The mean wood collection time per day more than doubled (from 2.3 to 5.2 hours per household per day for either the women respondent and/or other household members who collect) from baseline to follow-up.

Households vary in how they gather fuel. At baseline, 48% of women report they collect wood, and those that do average about an hour and a quarter a day on that task. 46% of women report others in their household collect wood, again averaging a little over an hour and a quarter a day. 39% of respondents both gather and report others in their household gather wood. 76% of households report either gathering or purchasing wood, while 46% report they buy wood and another 20% both gather and purchase wood.

While gathering wood takes time, cooking takes far more. Women report spending an average of 5 hours a day cooking, of which about 3 is next to the fire. Given that half the women spend an average of an additional 1½ hours a day gathering fuel, these activities take up the bulk of respondents' productive time.

Children also suffer from emissions from cook fires. About one seventh (15%) of the cooks we observed had a child on her back while cooking.[7] At baseline 77% of women reported sometimes or always having their children present when they cook, 31% reported sometimes having their children on their back when they cook, and 23% report that at least some of the time when they cook their children play near the fire. Finally, 15% of our sample at baseline report that one of their children has, at one point, been burnt by the cook fire.

The result of long exposure to the fire is high exposure to carbon monoxide. The average CO exposure for control women is 6.50 PPM/hour at the follow-up.[8] Multiplying the 6.50 CO ppm / hour average in our sample over the lunch meal times the 5 hours daily women report cooking implies women in our sample are exposed to approximately 32.5 ppm of CO daily. This is 130% of the recommended 25 ppm limit for an 8-hour exposure recommended by the World Health Organization (Penney, 1998).

It is possible cooks are exposed to less carbon monoxide when they are not sitting next to the cookfire (Recall on average women report spending 3/5ths of their cooking time next to the fire.) Even if we adjust the estimate of 32.5 ppm of CO exposure per day down by 20% to 26 ppm per day, the exposure remains above of the WHO recommended maximum daily exposure. Finally, this daily level is roughly equivalent to the carbon monoxide exposure from smoking the equivalent of 32 cigarettes or 1.5 packs of cigarettes a week (Meddleton *et*

[7] Observations were drawn on the sub-sample the women who wore the CO tube over the lunch meal (n=275).

[8] Note in Table 3b the CO PPM/hour level at baseline is significantly higher for both groups-24.60. We believe this is due to a truncation of the hours spent cooking variable and an over-estimation due to measurement error from starting late at the baseline survey.

*al.*2000).[9]

Consistent with high smoke exposure, at baseline women reported an average of 3.12 mean (4 median) of the four non-respiratory symptoms associated with cooking –including eye irritation, headache, throat irritation, and backache. The average declined to 2.88 symptoms (4 median), 8% below baseline, at the follow-up.[10] In addition, at the sixth month follow-up when enumerators observed cooking for the subset of women who took the CO survey, 30% of women had visibly irritated eyes.[11]

Control respondents at the follow-up report an average of 3.93 of the seven respiratory illness symptoms we asked about (cough, sore throat, fever, stuffy nose, trouble breathing, chest heaviness and/or coughed up mucus). In contrast, these women reported a third fewer symptoms for their husbands (2.20, which is statistically significant less than their wives, $P < .01$). It is plausible that exposure to the cookfire is responsible much of the women's higher average number of symptoms, although higher awareness of their own symptoms may also play a role.

Averaging over all children under 5 in the household, control children had a mean of 2.51 of four respiratory at the baseline.

The number of respiratory symptoms women reported rose between the baseline and midline: by 25% for the respondents and by 19% for their children (both increases statistically significant at $P < .01$). This increase was probably a regular seasonal change, as the April baseline survey was near the end of the dry season and while the October follow-up directly followed the rainy season.

Impacts

Solar Oven Usage

We installed stove usage monitors during the first month treatments had the solar oven. The stove usage monitors recorded treatments used their solar ovens on only 10% of days.

This low usage led Tostan staff to perform intensive training in the villages. The training consisted of solar oven trainers visiting women in the treatment group individually and collectively to conduct training on how to cook different meals with the solar oven.

In the sixth month of having the stove, SUMs measured use on 18% of stoves per day. During both months of measurement the weather was sunny enough for the oven to be used almost every day in almost every village.

It is unclear if the training was responsible for the near doubling of usage from the first to the sixth month. In our companion paper (Beltramo and Levine 2010) we do not find attending training predicted later stove usage.

Two villages near the sea had continued low usage even in the sixth month (of 8%, which is less than the mean of the other 18 villages of 19%, $P < .01$). This low usage was

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[9] This estimate is based on the Meddleton *et al.,* 2000 medical study measuring CO ppm of smokers versus non-smokers quantify that non-smokers. For a simple proxy to understand the relationship between the amount of CO ppm/hour women were observed to inhale and the illustrative equivalent of number of cigarettes smoke; if we make the assumption that the level of CO ppm inhaled is linear to the number of cigarettes smoked, based on this study every cigarette smoked has the equivalent effect of 1 CO ppm additional inhaled.

[10] The decline in the mean is statistically significant ($P<.05$).

[11] Data on the subsample with CO tubes at the follow-up.

due to regular wind from the sea that diminished the ability of the solar oven to cook.

Because the solar ovens can be used only during daylight hours, we anticipated they would be used primarily to cook the lunch meal, which is typically served between 2-3 p.m. The lunch meal in Senegal is traditionally the largest meal of the day and would provide the best opportunity to reduce fuel consumption and smoke exposure.

On the follow-up survey only 7% of our sample reported using the solar oven to prepare part or all of the lunch meal. When we observed cooking during the CO survey, every cook who was using the solar oven also had an additional wood or charcoal fire lit.

The main barrier to cooking lunch solely with the solar oven appears to have been size. When we asked for complaints about the solar oven, by far the most important was that the size was too small (50% of responses).[12] This complaint fits with the high number of people our sample cook for; as noted above, at baseline about 90% of respondents reported cooking for more than six people (the capacity of the solar oven).[13]

Further, when we account for the OECD adult age equivalent of 6 adults, which is equal to 3.5 persons, 88% of our sample have the adult age equivalent of households greater than 6 persons or less. Thus, it is clear that the size of the stove remains a substantial issue for nearly 90% of our sample who have a 3.6 “adult equivalent” persons or more in their household.

Given the small size, households rarely reported cooking the main lunch meal with the solar oven. Instead the majority of households used the solar oven to prepare the (usually smaller) dinner meal (40%), snack (28%), and separate meals for children or diabetics (13%).[14] In addition, at the follow-up survey, of all households using the solar oven, 61% were using it to prepare dinner. As it is a common practice to pre-cook meals and then reheat them at meal time, cooking dinner concurrently with lunch proved both convenient and consistent with familiar cooking methods.

Finally, the stove usage monitors proved critical in measuring objective stove usage. Solar oven users at the six month follow-up report using their solar oven 38% of days, double the SUM-measured usage rate of 18%. When we observed stove usage at the six month follow-up, for the 17 of the 20 villages where the weather was sunny, we found 61% of women were using their solar ovens– or more than 3 times the average usage rate on days they did not anticipate our visit. There is clearly a role for SUM’s in future studies.

Wood Usage

Table 5 presents the core regression results on fuel usage. Across many specifications, the point estimates shows a small decline in wood usage among medium-sized (7-12 people) households that received the solar oven, but not for treatment households of other sizes.

In the first model we interact treatment with three household size categories. Households of size 7-12 persons in the treatment group showed a statistically significant drop in daily wood use of 1.4 kilograms per day (about 14% of the mean). Households of 6

[12] The other common complaints were that it cooked too slowly (35%) and was not durable (11%).

[13] An additional constraint to cooking lunch could be the solar oven which is a slow cooker requires a behavior change in how women cook the widely popular lunch meal ceebu jën (Beltramo and Levine 2010), and in particular require women to simmer instead of fry the rice for similar but not equal taste.

[14] Data is from the follow-up survey, referring to the most frequent meal which women prepare with their solar oven. The dinner meal, which is often porridge, is well suited for solar cooking with the solar oven.

persons or less or 13 and more do not show any economically statistically significant change in fuel use.

In column 2 we add baseline control variables such as wood usage and measures of income. The point estimates are almost identical as in column 1.

We are concerned that the number of people a woman cooks for may change when she receives a solar oven. Thus, in column 3 we instrument for the number of people women report cooking for at the follow-up with the number they report cooking for at baseline (and the various interactions with treatment status). The number of people women report cooking for on the follow-up is statistically significant ($P<.001$) for both household dummy 7-12 persons and 13 persons or more, which suggests we have a strong first stage. Our results are consistent with the OLS results (see Table 5 column 3).

To test if changing household size into adult age equivalent has an effect on our results, we reran the models in Table 4 but replaced the 3 size categories <6, 7-12, and 13 or more with small, medium, and large adult equivalent household sizes. Results were largely unchanged.

With the new size controls we continue to find no evidence of a main effect of treatment (corresponding to model 1). When we examine treatment interacted with adult equivalent size of household terciles, the coefficient is significantly negative for the small household size (1.8-4.2 adult equivalents or the equivalent of 2 adults and 1 child to 7 adults and 1 child). Small treatment households show a statistically significant drop (95%) in daily wood use of between -0.31 to -0.42 kg. depending on the specification, equaling about 4% savings. This effect is approximately one third the 14% drop among treatment households with 7-12 persons in Table 5.

We do not know why interacting treatment with adult equivalent household size shows a smaller drop in wood use than with the unadjusted household size.[15] What is fairly consistent across the two measures of household size is that some, but not all, smaller households experienced lower fuel use with the solar oven.

To check robustness we measured kilograms of wood use four ways: used all day yesterday, used all day yesterday per capita, used preparing yesterday's lunch, and used for yesterday's lunch per capita. In all cases, results were similar to those in Table 5.

Time spent collecting fuel and cooking

The regression results show a small point estimate drop for the treatment effect on the time spent collecting fuels only for households of size 6 persons or less but the coefficient is not statistically significant (see Table 6, col. 1).

Results are similarly unimpressive for time spent next to the cook fire. In comparing the treatments and controls (see Table 4) and in the regression models (see Table 6, col. 2), treatment status had no detectable effect on the time women spend next to the cook fire.

To check robustness, we reran the time spent collecting wood models separately on the women's time and the time of others in her household. Results were unchanged. As with kilograms of wood used, we test treatment interacted with terciles of the number of adult equivalents. None of the interactions are statistically significant. Finally, we run total

[15] One hypothesis is that adult age equivalent is based on household lists of individuals from the baseline survey while the household size categories are based on number of people women cook for from the sixth month follow-up (which was often provided by a different respondent).

household time collecting wood constrained by only those whose wood collected lasts less than 2 weeks and find that treatment interacted with households of size 13 persons or more has a coefficient of 207 minutes per week (>4 hours/week) P<.05.

Carbon Monoxide Exposure

In the follow-up survey 166 treatment households and 109 control households received the CO tube. The mean for the control group 6.50 and for the treatment group is 8.09 ppm/hour. The unexpectedly *higher* CO exposure among treatments is marginally statistically significant at the 10% level.

The regression analysis shows that the marginally significant difference in means is largely due to small households (Table 6, col. 3). The coefficient on the interaction of treatment times the woman cooks for 6 persons or less is 6.5 CO PPM/hour, which is statistically significant at the 5% level. Our sample is small (only 20 treatments with CO tubes had household size 6 or under), but the result is not due to outliers; this group has substantially higher median CO readings than the other groups.

As before, we replace our 3 categories of the number of people cooked for with the three groupings of adult equivalents (and their interactions with treatment). Carbon monoxide exposure was higher by 1.31-1.59 CO PPM / hour for households with 1.8 to 4.2 adult equivalents (the smallest adult-equivalent size tercile). This increase is between 20-24% of the mean control CO exposure. The results that small households in the treatment group are exposed to more carbon monoxide than controls is puzzling.

Self-Reported Health

In the regression analysis (Table 6, col. 4-6), we analyze women's reports of symptoms for themselves and their children with controls for village, baseline number cooked for, several other baseline characteristics, and the women's reports of their husbands' respiratory symptoms.

For the count of 4 symptoms associated with cooking (eye irritation, headache, sore eyes, and back ache) there is no statistically significant difference between the treatment and control group (col. 4). The coefficients of the three household size categories * treatment are all small and of mixed sign.

When we repeat the regression predicting the women's self-reported respiratory symptoms, we again find no significant differences between the treatment and control group (Table 6, col. 5).

Finally, we repeat the regression predicting the women's reports of under-five children's respiratory symptoms (averaged within the household; Table 6, col. 5). Here, we find significant differences between the treatment and control group, but in the opposite direction from what we anticipated. Specifically, children aged 5 and under in households with 13 or more people have 0.30 more symptoms (SE = .13, P < .01) if they are in a treatment household than if they are in a similarly large control household. We do not want to make too much of this result, as the 3 household size * treatment indicators are jointly not significant (P < .19).

In robustness checks we controlled for whether the women enrolled in the program are part of a polygamous household, and a dummy variable for whether she is employed or not. We removed the endogenous cooking in an enclosed or semi-enclosed hut. We ran the entire set of regression specifications individually for each of the four symptoms associated with cooking and for each of the seven respiratory symptoms. Results were largely unchanged.

Compounds with multiple study participants

In this section, we study only compounds with more than one study participant per compound, as 33% of our randomized households (260) are part of multi-household compounds.

In Table 7 we present runs similar to those in Tables 5 and 6 focusing only on this subsample. We compare compounds with 2 or more treatments to those with multiple controls or with 1 treatment and one or more control. (The sample size is too small to look only at compounds that only had controls.)

Results are very similar to those in the full sample. There is a statistically significant decline of 1.6 kilograms a day of wood use for households with 7-12 people (col. 1), which is similar to the 1.4 kilogram decline in the full sample (Table 5, col. 1). There remains no statistically significant improvement in time by the cookfire, time gathering wood, or self-reported symptoms related to cooking or respiratory symptoms (columns 2, 3, 5 and 6). The surprising increase in exposure to carbon monoxide at treatment homes with 6 or fewer people also remains (col. 4), which is larger (but not statistically significantly different from) the estimate in the whole sample (Table 6, col. 3).

Conclusions

We conclude with a summary, caveats, and some implications.

Summary

Our sample suffers from the familiar ills of traditional biomass cookstoves. First, gathering fuel and cooking take on average six hours a day. In addition, cooks are exposed to dangerous levels of smoke. The average of 130% of the daily recommended level of carbon monoxide we measure is roughly equivalent to the carbon monoxide from smoking 1.5 packs of cigarettes a week. Thus, it is not surprising that at the follow-up control women report an average of four of the 7 respiratory symptoms we asked about (fever; sore throat; runny or stuffy nose; cough; wheezing; woke up with chest heaviness; coughed up mucus)—almost twice the rate they report for their husbands.

Though the solar ovens were attractive to consumers (at a heavily subsidized price), the ovens were used irregularly by most households. The stove usage monitor recorded usage of the solar ovens on 19% of days during the sixth month. While modest, this usage rate is double that of the first month (10%). Some of the increase may have been due to intensive village training by stove specialists or just due to households learning how best to use the solar oven. Additional hypotheses for the low usage are explored in a companion paper (Beltramo and Levine 2010).

Low usage is not surprising given nearly 80% of our households report cooking for more than six people. Because the solar ovens are usually too small, during the sixth month village visit we observed all women in the treatment group cooking with a traditional stove at the same time as they were using the solar oven.

On average there was no detectable decline in wood usage for treatment homes. At the same time, there was a small decline in wood usage for medium-sized (7-12 people) households, and in some specifications for all households 12 and under. Consistent with low usage of the solar oven and continued usage of traditional stoves, there was no detectable effect of solar ovens on, time spent collecting fuel, or on time spent next to the cook fire. There is no evidence solar ovens reduce exposure to carbon monoxide or self-reported respiratory symptoms such as coughs and sore throats.

Caveats

Numerous issues arose in our data collection that caution against over-confidence in our precise results. Some issues are familiar to most randomized trials, while a few arose due to the complexities of fuel use, cooking, and eating in our study population.

- Randomization was supposed to be limited to one woman per compound. In fact, many compounds had more than one participant.
- There was non-random attrition of (fortunately only) a few percent of the sample.
- There was non-random missing data of a more significant share of the sample.
- Our data collection was organized around the "household," but in many compounds women rotate cooking duties across meals or days with their co-wives and other compound members. In addition, children and adults often move in complex patterns, using different stoves within and across compounds.
- We placed the carbon monoxide tubes only on woman intending to light a fire that day, but did not retain the count of women who were not lighting a fire.
- The carbon monoxide tubes measured CO exposure during the middle of the day, when most cooks prepare lunch. Thus, we missed any reduction in evening smoke inhalation among women who used the solar oven to pre-cook dinner.

Each of these issues limits our confidence in the precise numbers we report. At the same time, we believe each issue has only a small effect, so the measured results are close to what occurred.

Implications

Our research has several implications for those distributing improved cookstoves and for evaluations of such projects.

Implications for improved cookstove projects

The lessons from this study for improved cookstoves projects are familiar (e.g., Duflo *et al.,* 2007; Miller *et al.,* 2010): Adoption and usage of improved stoves will be higher if the new stove is the right size for the target market, cooks familiar recipes with little change in recipes; is convenient to use; maintains perceived food quality; and saves fuel whose value (in time and/or money) outweighs the full cost of the stove.

Implications for evaluations

SHE did an above-average needs assessment prior to this pilot, including qualitative interviews and feasibility tests to ensure consumers needs were compatible with the solar ovens at the price the NGOs had chosen ($23). Nevertheless, many of our key results were available without the randomized controlled trial of almost 1000 homes. For example, if the needs assessment had observed ongoing usage of older cookstoves even for cooks using the solar overn, the NGOs might have refocused their programs without rolling out to 1000 customers: Tostan could have chosen a different improved cookstove for rural Senegal, while SHE could have opted to pilot this solar oven in an African region with smaller households. More generally, many development projects can benefit from richer feedback from consumers (or students, patients, and so forth) to understand how stakeholders experience the project.

Both needs assessments and statistical studies will need to measure usage of new stoves. In our study both self-reported usage and direct observation (on a day consumers knew the data collection team was coming) measured double or more usage of the new stove than the less obtrusive real-time stove usage monitor (SUM). Thus, it was crucial to have objective

SUMs (Ruiz *et al.*, 2008).

Reductions in exposure to emissions and in the release of greenhouse gases depends not just on high usage of the new stove, but also on low usage of older biomass stoves. Thus, SUMs should be placed on all of a user's stoves, not just the new stove.

While the solar oven was not successful in reducing wood use or carbon monoxide exposure much in this setting, the evaluation was successful. As noted, above, the early results of this evaluation stopped the NGOs from scaling up the distribution of the solar ovens. A familiar piece of advice for all development programs is to follow the example of Tostan and SHE and build good evaluations into pilots prior to scaling up.

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