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LETTER

# Can economic incentives enhance adoption and use of a household energy technology? Evidence from a pilot study in Cambodia

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## Abstract

While much work has examined approaches to increase uptake of a variety of household environmental, health, and energy technologies, researchers and policymakers alike have struggled to ensure long-term use. Drawing on a pilot-scale experiment conducted in rural Cambodia, this study evaluates whether economic incentives enhance continued use of—and fuel savings from—improved cookstoves (ICS). Capital-cost subsidies that have been traditionally employed to enhance ICS adoption were augmented with rebates linked to stated and objectively measured use in order to investigate impacts on both initial and sustained adoption in the treatment group. Results show that households do respond to these rebates by adopting the intervention ICS at significantly higher rates, and by using it more frequently and for longer periods. Consistent with these stove-use patterns, solid-fuel use and time spent collecting or preparing fuels also decline. However, this effect appears to diminish over time. Thus, while economic inducements may significantly increase adoption and use of new environmental health technologies, corresponding reductions in environmental or livelihood burdens are not guaranteed. Additional research on the design and implementation of incentive-based interventions targeting households directly—such as carbon financing or other forms of results-based financing (RBF) for improved cookstoves—therefore seems warranted prior to wider implementation of such solutions.

## 1. Introduction

The promotion of new technologies that promise welfare improvements in low-income settings has preoccupied policymakers and researchers for decades (Besley and Case 1993). Interventions aimed at increasing uptake, however, often fail to meet expectations, and the developing world is littered with well-intentioned technologies that were either not adopted or eventually abandoned by their intended beneficiaries[6]. Much work in the past has wrestled with this challenge; in particular, researchers have drawn on insights from field experiments to identify policy levers that may improve uptake (Ashraf *et al* 2010, Cohen and Dupas 2010, Giné and Yang 2009, Miller and Mobarak 2015, Pattanayak *et al* 2009, Tarozzi *et al* 2014). These experiments aim to ensure widespread adoption of technologies by reducing their acquisition costs—monetary and otherwise. While this work has greatly advanced understanding of initial adoption (the extensive margin), the recent literature is relatively silent on what drives sustained high levels of use (the intensive margin). Needless to say, obstacles to sustained use continue to compromise the effectiveness of many technologies and, thus, represent a prominent knowledge gap (Bensch and Peters 2015).

The challenge of moving from traditional to clean technologies is particularly acute for energy-poor

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[6] A recent article in the New York Times (Gettleman 2015) on the use of fine-mesh mosquito nets—intended as a technological solution to reduce the spread of malaria—for fishing in Zambia received considerable attention, and is emblematic of the unexpected challenges associated with adoption and sustained use of beneficial environmental health technologies.

households in the developing world. Nearly three billion people cook and heat their homes with solid fuels in traditional stoves or open fires. The resulting household air pollution causes over four million deaths annually, a health burden borne largely by the poor, women, and children (World Health Organization 2016). Inefficient combustion of solid fuels also emits pollutants that are among the most significant contributors to climate change, including carbon dioxide, methane, and black carbon (Bond *et al* 2013), which is already impacting millions by disrupting weather patterns, accelerating glacial melt, and causing a range of damages that extend well beyond health (Menon *et al* 2002, Srivastava *et al* 2012)[7].

Improved cookstoves (ICS) have long been envisioned as a solution to this multifaceted problem (Ruiz-Mercado *et al* 2011). Despite significant heterogeneity in cost, quality, and materials, generally speaking ICS are designed to reduce emissions by increasing combustive efficiency. In so doing, ICS are expected to yield health benefits, and also reduce the total amount of biomass required, easing stress on local forests (a common source of fuelwood) and the global commons (through lowered climate-altering emissions). Where fuelwood extraction is unsustainable, ICS interventions may also help maintain forest carbon stocks (Maes and Verbist 2012)[8]. These benefits, however, depend on sustained use[9]. Indeed, diminishing or improper use of ICS may entail little to no benefits (Hanna *et al* 2016), or even exacerbate an already inferior environmental equilibrium (Nepal *et al* 2011). This is not an insignificant problem, either; research increasingly highlights that 'stacking' of polluting and improved technologies is nearly ubiquitous (Brooks *et al* 2016, Masera *et al* 2000, Piedrahita *et al* 2016, Ruiz-Mercado and Masera 2015), and that this behavior can compromise emissions reductions (Aung *et al* 2016, Johnson and Chiang 2015).

How can the adoption and use of ICS be encouraged in ways that ensure expected environmental and health benefits are realized? We present results from a pilot study in rural Cambodia that tests whether and how economic incentives increase use of an ICS. Specifically, we augment capital-cost subsidies—traditionally employed to enhance adoption among the poor—with rebates linked to technology use, and evaluate the impact these economic incentives have on both initial adoption and sustained use. We find that households offered rebates used the intervention ICS more frequently and for longer periods than those who were not. We also observe initial reductions in consumption of solid fuels and time spent collecting or preparing fuels, though these impacts diminish over time. Our results suggest that the effectiveness of capital subsidies may be significantly enhanced by relatively simple monetary inducements. Nonetheless, policymakers must also consider the implications of behavioral responses to these incentives, as increased adoption and use do not necessarily translate into sustained environmental or livelihood benefits. Our study provides a promising launch pad for future research on these issues, given the growing interest in and use of incentive-based interventions such as carbon financing or other forms of results-based financing (RBF) for ICS[10].

## 2. A conceptual model of adoption of ICS

To motivate how economic incentives could enhance use of ICS, we draw on a model of household production of environmental quality and health (Grossman 1972, Pattanayak and Pfaff 2009). This framework helps explain (i) the detrimental effects of household air pollution exposure, and (ii) the effects of interventions that aim to reduce it (Jeuland *et al* 2015). Decisions to adopt technologies such as ICS are made by households on the basis of perceived private benefits (e.g. averting health risks or the drudgery of fuel collection)[11]. These decisions involve trade-offs with consumption and leisure.

According to this model, households maximize utility by allocating resources—time and money—to consumption, health 'risk-averting behavior,' and leisure. Initial resource endowments and the supply-side context constrain the set of available alternatives, and thus affect investments in health-improving technologies. The choices households make also depend on preferences; the effectiveness of averting behavior in reducing utility-harming illness and pollution (which varies with technology and the pollution context); and the extent to which households value environmental quality, namely clean air. Illness declines with increased household environmental quality and averting behavior, and with the pollution-reducing actions of others. Environmental quality improves with averting behavior, but is harmed by consumption, which generates pollution.

This micro-level perspective offers insights about how to best target and test the effectiveness of policies to

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[7] For instance, Burney and Ramanathan (2014) find that up to ninety percent of agricultural losses in India over 1980–2010 can be explained by so-called 'short-lived climate pollutants' (such as black carbon) alone while Jeuland and Tan Soo (2016) find that health is a modest piece of the household air pollution calculus, contrary to what the health focus of this literature would seem to suggest.

[8] See Jeuland and Pattanayak (2012) for an overview of the costs and benefits associated with ICS.

[9] We note that expected ICS benefits do not depend exclusively on stove-use patterns. Factors such as stove design, fuel type, and emissions-reduction potential are also critical (Kshirsagar and Kalamkar 2014).

[10] A thorough analysis of the role of RBF in household energy transitions is beyond the scope of this study. We point to Freeman and Zerriffi (2014), who evaluate the potential for carbon credits to support cookstove projects and deliver 'win-win' environmental and development benefits.

[11] This framework treats the household as a single economic unit. However, various factors may cause deviations from this conceptualization of the decision-making process, such as intra-household gender dynamics (Ryan 2014).

increase adoption and use of averting behavior. Given that investments in beneficial technologies are restricted by the availability of inputs of time, materials, and knowledge (Jeuland *et al* 2015), reductions in the costs of these inputs are predicted to increase averting behavior, all else being equal. Interventions aiming to increase uptake have traditionally seen costs as static, however, requiring a one-time subsidy or knowledge dissemination campaign. Dynamic incentives (namely, rebates linked to use over time) have received relatively less attention but may be a promising alternative.

The impacts of incentive-based interventions, however, are not always clear *ex ante*. For instance, monetary incentives may induce cheating by beneficiaries (Gravelle *et al* 2010). Others have investigated whether and how incentives have unintended consequences (Oxman and Fretheim 2009), such as inducing rebound by reducing the relative prices of pollution-generating activities (Davis *et al* 2014). In addition, the evidence on direct payments as a tool to enhance uptake of environmental health technologies is mixed (e.g. Krezanoski *et al* 2010). We add to the literature by evaluating the extent to which dynamic incentives can augment the effectiveness of more traditional one-time subsidies in the context of household energy interventions that deliver environmental and health benefits.

## 3. Methodology

### 3.1. Study sites and sample selection

Our study took place in two districts of Kandal Province, Cambodia, in July-August 2015. We identified four rural communities with prior exposure to activities led by our field partner[12]. One community was randomly designated as a 'control' community while the remaining three were randomly assigned to one of three 'treatment' groups: Low; Medium; and High.

Approximately fifteen households were randomly selected in each community, yielding an initial sample of 61 households and final sample of 59 households (following household attrition). Baseline surveys were conducted with the full sample of households shortly after recruitment[13].

### 3.2. Description of control and treatment arms

Each household in the control community was invited to participate in a private ICS demonstration, after which it was offered the option to keep the device for one month at zero cost. Households were informed that at the end of the study period, they could purchase the ICS for USD 50 (reflecting a two-third subsidy relative to its full cost) or return it for free.

A Maxim iButton DS1922L stove-use monitor (SUM) was attached to each intervention stove distributed in the control community; households' existing cooking technologies were not monitored using these devices. The SUMs recorded timestamps and temperature (±0.5 °C) at five-minute intervals for the entire study period, yielding stove-use data. For the remainder of the study period, households in the control community received only weekly phone calls to confirm that their ICS remained functional.

Households in the treatment-low community were offered the same package—including the use of SUMs to monitor stove use—with one important modification. Specifically, they were informed that they would receive unannounced weekly visits to check stove use; for each week of verified stove use, they would receive a USD 12.50 (25 percent) rebate. Thus, households could effectively 'use off' the cost of the stove over the month-long study period. During weekly visits, the field team asked households a simple yes-or-no question about whether the stove had been used 'regularly' since the previous visit; upon answering affirmatively, households were informed that they had successfully earned the rebate.

Instead of verbally stating their stove-use behavior, households in the treatment-medium community were instructed to maintain daily stove-use diaries, which were distributed to them at the time of stove delivery. Households were informed that weekly follow-up visits would entail a diary check, and that the 25 percent rebate would be earned if they were found to be using the stove at least 2.5 times per day on average since the previous visit. If they met this threshold, households were informed that they had successfully earned the weekly rebate[14].

Finally, households in the treatment-high community were explicitly informed that the SUM attached to their stoves would 'count' use; rebates would be earned if measured stove-use indicated an average of at least 2.5 times per day since the previous visit. During weekly visits, the field team checked the SUM data and informed households whether they had successfully met the rebate threshold[15].

Thus, instead of increasing the rebate amount offered across treatment communities to elicit differential responses in stove-use behavior, we effectively varied the 'intensity' of effort required to

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[12] Our partner, SNV Cambodia, has been active in the country for over a decade, and leads a diverse set of initiatives in the agriculture, water, sanitation and hygiene, and renewable energy sectors. SNV (2016) provides an overview of local energy-use patterns and its ICS promotion activities.

[13] We piloted our survey instrument and incentive-based treatment in a separate community with a smaller group of households prior to rolling out the intervention in our sample communities.

[14] No attempt was made to verify whether diary-reported use matched actual use during these visits. In addition, rebates were not withheld for 'creative accounting' (such as filling out the diary days into the future)—if stove use as reported in the diary over the relevant period was found to have exceeded the threshold, households earned the rebate.

[15] There is a rich literature on the use of incentives to change behavior (Gneezy *et al* 2011). Our study design combines these insights with those from recent research on objective monitoring of environmental health technologies, which finds that households generally over-report use (Thomas *et al* 2013, Wilson *et al* 2015).

Table 1. Overview of control and treatment arms.

| | Control | Treatment-Low | Treatment-Medium | Treatment-High |
|---|---|---|---|---|
| **Capital subsidy**[†] | ✓ | ✓ | ✓ | ✓ |
| **Stove-use Monitor (SUM) attached to ICS** | ✓ | ✓ | ✓ | ✓ |
| **Weekly use-based rebates available** | | ✓ | ✓ | ✓ |
| **Weekly rebate amount**[‡] | | USD 12.50 | USD 12.50 | USD 12.50 |
| **Stove use verification mechanism over weekly monitoring period** | | Verbal affirmation of 'regular' stove use | Check of stove-use diary to verify reported stove use meets daily threshold | Check of SUM-measured data to verify stove use meets daily threshold |

[†] For our intervention, we used the ACE-1 stove, an 'ultra-clean' forced-draft biomass cookstove manufactured by African Clean Energy. The full cost of this device is USD 150. Households were offered a price of USD 50, representing a two-third subsidy relative to the full cost.

[‡] This represents a 25 percent weekly rebate relative to the post-subsidy price of the stove. Thus, households could effectively 'use off' the cost of the stove over the month-long study period.

earn the rebate by changing the monitoring mechanism. Households in the treatment-low community faced the least stringent monitoring, while those in the treatment-high community faced the strictest. Table 1 provides an overview of our control and treatment arms.

### 3.3. Outcomes of interest

We are primarily interested in the impact of economic incentives on four outcomes: (i) stove adoption; (ii) frequency and duration of stove use; (iii) solid-fuel use; and (iv) total time spent collecting or preparing fuel.

#### *(i) Stove adoption*

Despite their widespread use, the evidence on capital subsidies as a tool to increase adoption of ICS remains mixed (e.g. Mobarak *et al* 2012). Our study design enables us to compare outcomes for control households (who only received capital subsidies) with those for households who also received use-based incentives.

#### *(ii) Frequency and duration of improved-stove use*

We construct two objective measures of stove use frequency and duration for the ICS used in our study with data obtained from the SUMs. The first ('threshold') identifies a cooking event for each instance in which SUM-measured temperature crossed above and then below a predetermined temperature threshold (our preferred threshold is 50 °C)[16]. Using time stamps from the beginning and end of each cooking event, we estimate its duration. While approximate, the threshold approach provides a useful comparison for our second ('slope') measure. We assume that SUM-measured temperature increases and decreases more rapidly immediately when the stove is turned on and off than it does as a result of other changes in the ambient temperature. The slope approach, thus, identifies the beginning of a cooking event based on the slope of the SUM-measured temperature series being sufficiently positive, and its end based on the slope being sufficiently negative[17]. Having identified the beginning and end of a cooking event, we measure duration using timestamps.

#### *(iii) Solid fuel consumption*

In both baseline and end-line surveys, households were asked about fuel-use amounts for each of the fuels they reported using. In the case of solid fuels, this is an estimate of the mass consumed over a fixed period. Acknowledging that respondents may have limited ability to provide accurate measures, we augment these self-reported estimates with an objective measure of fuel use. Respondents were asked to collect an amount of solid fuel that was slightly more than what they expected to consume over the next 24 h. This amount, recorded in both rounds, was weighed by enumerators, who returned the next day to reweigh the remaining unused amount.

#### *(iv) Total time spent collecting or preparing biomass for combustion*

The drudgery of collecting and preparing biomass fuels and its associated impacts have featured prominently in the literature. More fuel (and thus time) is required when households rely on inefficient stoves, and this burden is usually borne by women and children, who have less time to devote to education and income-producing activities (Cabraal *et al* 2005, Lewis and Pattanayak 2012). To measure changes in time allocation, we enquired about time spent

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[16] As a test of robustness, we repeat our threshold analyses with a 40 °C and a 60 °C threshold. Results from these additional analyses largely match those obtained using our preferred specification.

[17] In our preferred specification, a cooking event is coded as having started when the mean increase in SUM-measured temperature over a ten-minute interval exceeds 0.5 °C per minute; a cooking event is coded as having ended once the weighted mean decrease in temperature over a ten-minute interval exceeds 0.4 °C per minute. As in the threshold approach, we rerun our analyses with a variety of alternate specifications that vary the covered time interval as well as the slope cut-off levels.

Table 2. Descriptive statistics, by treatment status.

| VARIABLES | (a) Full sample | | | (b) Control | | | (c) Treatment | | |
|---|---|---|---|---|---|---|---|---|---|
| | MEAN | STD DEV | N | MEAN | STD DEV | N | MEAN | STD DEV | N |
| SOCIOECONOMIC STATUS | | | | | | | | | |
| Relative wealth perception (out of 5) | 2.95 | 0.75 | 59 | 2.79 | 0.80 | 14 | 3 | 0.74 | 45 |
| Total expenditure (USD per month) | 292.5 | 130.5 | 59 | 246.1 | 130.6 | 14 | 307.0 | 128.5 | 45 |
| Number of rooms | 2.46 | 1.06 | 54 | 2.90 | 0.88 | 10 | 2.36 | 1.08 | 44 |
| HEAD OF HOUSEHOLD | | | | | | | | | |
| Female | 0.19 | 0.39 | 59 | 0.21 | 0.43 | 14 | 0.18 | 0.39 | 45 |
| Age (years) | 50.1 | 13.3 | 59 | 54.5 | 11.2 | 14 | 48.7 | 13.8 | 45 |
| Education (years) | 5.71 | 3.62 | 56 | 5.21 | 4.32 | 14 | 5.88 | 3.40 | 42 |
| HOUSEHOLD CHARACTERISTICS | | | | | | | | | |
| Household size | 4.54 | 1.71 | 59 | 4.14 | 1.79 | 14 | 4.67 | 1.68 | 45 |
| Number of children under five | 0.39 | 0.59 | 59 | 0.43 | 0.76 | 14 | 0.38 | 0.53 | 45 |
| HOUSEHOLD INFRASTRUCTURE | | | | | | | | | |
| Access to toilet | 0.75 | 0.44 | 59 | 1 | 0 | 14 | 0.67 | 0.48 | 45 |
| Access to private tap water | 0.42 | 0.50 | 59 | 0 | 0 | 14 | 0.56 | 0.50 | 45 |
| Household took loan in past year | 0.63 | 0.49 | 59 | 0.43 | 0.51 | 14 | 0.69 | 0.47 | 45 |
| STOVE OWNERSHIP AND USE | | | | | | | | | |
| Owns traditional stove | 0.97 | 0.18 | 59 | 1 | 0 | 14 | 0.96 | 0.21 | 45 |
| 'Primary stove' is traditional stove | 0.93 | 0.25 | 59 | 0.93 | 0.27 | 14 | 0.93 | 0.25 | 45 |
| Owns LPG stove | 0.25 | 0.44 | 59 | 0.14 | 0.36 | 14 | 0.29 | 0.46 | 45 |
| Owns electric stove or electric rice cooker | 0.22 | 0.42 | 59 | 0.14 | 0.36 | 14 | 0.24 | 0.43 | 45 |
| Time spent cooking (hours per day) | 2.53 | 1.11 | 59 | 2.40 | 1.01 | 14 | 2.57 | 1.14 | 45 |
| Time spent cooking on traditional stove (hours per day) | 2.27 | 1.16 | 59 | 2.26 | 1.08 | 14 | 2.27 | 1.19 | 45 |
| FUEL USE | | | | | | | | | |
| Uses fuelwood | 0.95 | 0.22 | 59 | 1 | 0 | 14 | 0.93 | 0.25 | 45 |
| Charcoal | 0.24 | 0.43 | 59 | 0.071 | 0.27 | 14 | 0.29 | 0.46 | 45 |
| Kerosene | 0.10 | 0.30 | 59 | 0.071 | 0.27 | 14 | 0.11 | 0.32 | 45 |
| LPG | 0.24 | 0.43 | 59 | 0.14 | 0.36 | 14 | 0.27 | 0.45 | 45 |
| Electricity | 0.20 | 0.41 | 59 | 0.14 | 0.36 | 14 | 0.22 | 0.42 | 45 |
| Total time spent preparing fuels (hours per week) | 1.36 | 1.75 | 59 | 1.09 | 0.89 | 14 | 1.45 | 1.95 | 45 |
| Total time spent collecting fuels (hours per week) | 3.08 | 6.46 | 59 | 4.49 | 7.79 | 14 | 2.64 | 6.02 | 45 |
| PERCEPTIONS AND BELIEFS | | | | | | | | | |
| Awareness of improved stoves | 0.73 | 0.45 | 59 | 0.86 | 0.36 | 14 | 0.69 | 0.47 | 45 |
| Awareness of clean fuels | 0.80 | 0.41 | 59 | 0.93 | 0.27 | 14 | 0.76 | 0.43 | 45 |
| Health benefits (out of 5) | 4.28 | 0.88 | 47 | 4.15 | 1.28 | 13 | 4.32 | 0.68 | 34 |
| Environmental (local forest) benefits (out of 5) | 4.43 | 0.77 | 47 | 4.31 | 1.18 | 13 | 4.47 | 0.56 | 34 |
| Air quality benefits (out of 5) | 4.45 | 0.75 | 47 | 4.38 | 1.12 | 13 | 4.47 | 0.56 | 34 |

Note: 1 US dollar ≈ 4 000 Cambodian riel; LPG = liquefied petroleum gas.

collecting and preparing biomass fuels for cooking in both survey rounds.

## 4. Empirical strategy and results

### 4.1. Sample description

Table 2 outlines key characteristics of the households in our sample. The average household consists of 4.5 members and reports a monthly expenditure of approximately USD 300. The average household head is fifty years old, and has fewer than six years of education. Only nineteen percent of households in our sample are headed by women.

Households across treatment and control communities are observationally similar along key criteria, including the education level of the household head and household size. In addition, they appear to have very similar cooking behaviors. For instance, nearly all households own a 'traditional' stove and identify it as their 'primary stove.' Households spend similar amounts of time cooking—including, specifically, cooking on a traditional stove—which suggests that underlying cooking practices are comparable.

We note three important differences. First, treatment households report higher monthly expenditures. Second, no control household indicates access to private, in-house tap water[18]. Household expenditure and water-treatment behaviors have been found to be correlated with household-level decisions to adopt ICS (e.g. Alem *et al* 2014, Silk *et al* 2012). Finally, there are also differences across our intervention arms in ownership of LPG and electric stoves, and in awareness of clean stoves and fuels, perhaps due to prior clean-cooking interventions initiated by our field partner in the region. We control for these differences in our empirical analysis.

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[18] We are unable to verify whether this is a true difference or a result of a misunderstanding on the part of respondents or surveyors.

**Table 3.** Mean daily stove-use count.

| | (1) | | (2) | |
|---|---|---|---|---|
| VARIABLES | Daily stove-use count | Bootstrapped 90% CI | Daily stove-use count | Bootstrapped 90% CI |
| (a) Threshold approach (50 °C threshold) | | | | |
| Treatment | 1.21 | (−1.69, 4.11) | | |
| | [0.34] | | | |
| Low | | | $0.89^{*}$ | (0.18, 1.59) |
| | | | [0.058] | |
| Medium | | | 0.74 | (−0.11, 1.59) |
| | | | [0.14] | |
| High | | | $1.85^{**}$ | (1.12, 2.58) |
| | | | [0.012] | |
| Constant | $1.42^{*}$ | (0.39, 2.45) | $1.45^{**}$ | (0.66, 2.24) |
| | [0.051] | | [0.02] | |
| Household controls | Yes | | Yes | |
| Observations | 59 | | 59 | |
| R-squared | 0.28 | | 0.42 | |
| (b) Slope approach† | | | | |
| Treatment | 1.28 | (−0.53, 3.09) | | |
| | [0.18] | | | |
| Low | | | $1.01^{*}$ | (0.22, 1.80) |
| | | | [0.06] | |
| Medium | | | 0.60 | (−0.56, 1.76) |
| | | | [0.32] | |
| High | | | $1.89^{***}$ | (1.40, 2.38) |
| | | | [0.001] | |
| Constant | $1.69^{*}$ | (0.17, 3.20) | $1.76^{**}$ | (0.66, 2.85) |
| | [0.08] | | [0.03] | |
| Household controls | Yes | | Yes | |
| Observations | 59 | | 59 | |
| R-squared | 0.25 | | 0.33 | |

Note: The dependent variable is mean daily stove-use count, estimated using the threshold approach in panel (a) and using the slope approach in panel (b). Column (1) presents results for all households assigned to any of the three treatment arms; column (2) presents results for each of the three treatment arms separately. Household-level controls include: household size; monthly expenditure; access to private tap water; ownership of LPG stoves; ownership of electric stoves or rice cookers; and awareness of the existence of improved stoves or clean fuels. Pairs cluster-bootstrapped *p*-values shown in brackets and 90% confidence intervals shown in parentheses, with clustering at the village level (Cameron *et al* 2008, Esarey 2016). $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

† A cooking event is coded as having started when the mean increase in SUM-measured temperature over a ten-minute interval exceeds 0.5 °C per minute. A cooking event is coded as having ended once the weighted mean decrease in temperature over a ten-minute interval exceeds 0.4 °C per minute.

### 4.2. Stove adoption

Our first main result is that adoption rates differ across treatment and control communities. By the end of the study period, nearly all treatment households had successfully ‘used off’ the full price of their stove under the terms of the monitoring mechanism assigned to their respective communities, and chose to keep the stoves[19]. In contrast, none of the control households were willing to purchase the stoves at the subsidized price, instead choosing to return them at the conclusion of the study.

### 4.3. Frequency and duration of stove use

We next evaluate the impact of economic incentives on the frequency of stove use. Our linear regression model is specified as follows:

$$\begin{aligned} Y_{i,j} &= \beta_0 + \beta_1 LOW_j + \beta_2 MEDIUM_j \\ &+ \beta_3 HIGH_j + \mathbf{X}_i\gamma + \varepsilon_{i,j} \end{aligned} \qquad (1)$$

where $Y_{i,j}$ represents a SUMs-based measure of stove use for household $i$ in community $j$, and $LOW$, $MEDIUM$, and $HIGH$ are indicator variables for the respective treatment arms[20]. We also control for key household-level characteristics—namely, household size, monthly expenditure, access to private tap water, ownership of LPG and electric stoves, and awareness of improved stoves or fuels, represented by $\mathbf{X}_i$. Finally, $\varepsilon_{i,j}$ represents unobserved characteristics.

Results using a daily count of cooking events are reported in table 3. We do not detect aggregate differences between treatment and control households using the threshold-based measure of stove use (panel *a*, column 1). Disaggregating by treatment arm, however, we find a statistically significant effect of the intervention in the treatment-low and treatment-high

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[19] Specifically, only two treatment households faced a non-zero final stove price; one of these households rejected the offer to purchase at this price and returned the stove.

[20] As we omit the indicator variable for the control community in our specification, the coefficients on these variables should be interpreted as the impact of the respective economic-incentive-plus-monitoring intervention carried out in each community relative to the impact observed in the control community.

**Table 4.** Mean daily stove-use duration, minutes.

| | (1) | | (2) | |
|---|---|---|---|---|
| VARIABLES | Stove use duration | Bootstrapped 90% CI | Stove use duration | Bootstrapped 90% CI |
| (a) Threshold approach (50 °C threshold) | | | | |
| Treatment | 103.2 | (−558, 764) | | |
| | [0.58] | | | |
| Low | | | 23.0 | (−13, 59) |
| | | | [0.21] | |
| Medium | | | −19.8 | (−66, 26) |
| | | | [0.41] | |
| High | | | $265.9^{***}$ | (205, 327) |
| | | | [0.002] | |
| Constant | 108.1 | (−27, 243) | $115.5^{**}$ | (42, 189) |
| | [0.16] | | [0.04] | |
| Household controls | Yes | | Yes | |
| Observations | 59 | | 59 | |
| R-squared | 0.17 | | 0.59 | |
| (b) Slope approach[†] | | | | |
| Treatment | 13.6 | (−30, 57) | | |
| | [0.48] | | | |
| Low | | | 17.2 | (−17, 52) |
| | | | [0.32] | |
| Medium | | | −1.0 | (−53, 51) |
| | | | [0.97] | |
| High | | | 11.2 | (−22, 44) |
| | | | [0.47] | |
| Constant | $97.5^{**}$ | (49, 146) | $100.5^{***}$ | (61, 141) |
| | [0.02] | | [0.009] | |
| Household controls | Yes | | Yes | |
| Observations | 59 | | 59 | |
| R-squared | 0.21 | | 0.22 | |

Note: The dependent variable is mean daily stove-use duration in minutes, estimated using the threshold approach in panel (*a*) and using the slope approach in panel (*b*). Column (1) presents results for all households assigned to any of the three treatment arms; column (2) presents results for each of the three treatment arms separately. Household-level controls include: household size; monthly expenditure; access to private tap water; ownership of LPG stoves; ownership of electric stoves or rice cookers; and awareness of the existence of improved stoves or clean fuels. Pairs cluster-bootstrapped *p*-values shown in brackets and 90% confidence intervals shown in parentheses, with clustering at the village level (Cameron *et al* 2008, Esarey 2016). $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

[†] A cooking event is coded as having started when the mean increase in SUM-measured temperature over a ten-minute interval exceeds 0.5 °C per minute. A cooking event is coded as having ended once the weighted mean decrease in temperature over a ten-minute interval exceeds 0.4 °C per minute.

communities, where households used the stoves up to two more times each day (panel (*a*), column 2). In panel (*b*), we repeat the analysis with the slope-based measures, obtaining similar results.

Table 4 presents results for stove use duration. In line with stove-use count results, we do not detect aggregate differences between treatment and control households (panel (*a*), column 1). Disaggregating by treatment arms in column (2), however, we again find a significant effect of the intervention in the treatment-high community. These results are not robust; using stove-use duration measured via the slope approach in panel (*b*) yields estimates that are smaller and not statistically significant[21].

### 4.4. Biomass and solid fuel use

For logistical reasons, our baseline surveys (including fuel weighing) were conducted just after households were recruited and provided with improved stoves. We thus do not have objective data on fuel use prior to stove provision, i.e. the initial measures of fuel use already reflect changes that came with owning the improved stoves. Since we are interested in how rebates relate to trends in fuel use over time, we employ a difference-in-differences (DID) strategy, comparing differences in solid-fuel use between treatment and control households at the outset of the intervention and its conclusion. Our model is specified as follows:

$$\begin{aligned} Y_{i,j} = \beta_0 + \beta_1 PERIOD + \beta_2 LOW_j + \beta_3 MEDIUM_j \\ + \beta_4 HIGH_j + \beta_5 (PERIOD \times LOW_j) \\ + \beta_6 (PERIOD \times MEDIUM_j) \\ + \beta_7 (PERIOD \times HIGH_j) + \mathbf{X}_i \gamma + \varepsilon_{i,j}. \end{aligned} \quad (2)$$

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[21] Upon further inspection of these apparently inconsistent stove use patterns, we find that households in the treatment-high communities appear to be leaving stoves running for extended periods of time at different levels, a type of use behavior that the slope approach is unable to fully capture since the end of the cooking event might be mischaracterized. We return to the implications of such behavioral responses in section 5.

**Table 5.** Solid-fuel use, kilograms per day.

| | (1) | | (2) | | (3) | | (4) | |
|---|---|---|---|---|---|---|---|---|
| VARIABLES | Measured weight | Bootstrapped 90% CI | Measured weight | Bootstrapped 90% CI | Stated weight | Bootstrapped 90% CI | Stated weight | Bootstrapped 90% CI |
| Period | −1.90 | (−4.60, 0.80) | −1.90 | (−5.27, 1.48) | $-2.01^{***}$ | (−2.40, −1.62) | $-1.98^{***}$ | (−2.54, −1.42) |
| | [0.17] | | [0.25] | | [0.001] | | [0.003] | |
| Treatment | $-3.04^{**}$ | (−4.42, −1.66) | | | $-3.81^{**}$ | (−5.59, −2.03) | | |
| | [0.02] | | | | [0.02] | | | |
| Period × Treatment | 1.12 | (−1.65, 3.90) | | | 1.23 | (−1.25, 3.71) | | |
| | [0.37] | | | | [0.31] | | | |
| Low | | | $-3.28^{**}$ | (−5.46, −1.10) | | | $-4.45^{**}$ | (−6.27, −2.62) |
| | | | [0.045] | | | | [0.011] | |
| Medium | | | $-2.78^{**}$ | (−4.48, −1.07) | | | $-3.93^{**}$ | (−6.37, −1.49) |
| | | | [0.03] | | | | [0.03] | |
| High | | | $-3.14^{**}$ | (−4.44, −1.84) | | | $-3.05^{**}$ | (−4.99, −1.12) |
| | | | [0.011] | | | | [0.04] | |
| Period × Low | | | 1.44 | (−1.29, 4.17) | | | $2.09^{***}$ | (1.60, 2.59) |
| | | | [0.27] | | | | [0.003] | |
| Period × Medium | | | 0.14 | (−5.01, 5.29) | | | 0.32 | (−1.97, 2.60) |
| | | | [0.96] | | | | [0.72] | |
| Period × High | | | 1.59 | (−0.41, 3.61) | | | 0.81 | (−0.11, 1.72) |
| | | | [0.15] | | | | [0.13] | |
| Constant | $3.31^{**}$ | (1.51, 5.12) | $3.36^{**}$ | (1.48, 5.24) | $4.08^{**}$ | (1.42, 6.75) | $4.15^{**}$ | (2.02, 6.27) |
| | [0.02] | | [0.02] | | [0.04] | | [0.02] | |
| Household controls | Yes | | Yes | | Yes | | Yes | |
| Observations | 106 | | 106 | | 110 | | 110 | |
| R-squared | 0.29 | | 0.30 | | 0.31 | | 0.33 | |

Note: The dependent variable is daily use of solid fuels in kilograms, estimated using an objective 24 h weight measure in columns (1) and (2) and using household self-reports in columns (3) and (4). Columns (1) and (3) present results for all households assigned to any of the three treatment arms; columns (2) and (4) present results for each of the three treatment arms separately. Household-level controls include: household size; monthly expenditure; access to private tap water; ownership of LPG stoves; ownership of electric stoves or rice cookers; and awareness of the existence of improved stoves or clean fuels. Pairs cluster-bootstrapped *p*-values shown in brackets and 90% confidence intervals shown in parentheses, with clustering at the village level (Cameron *et al* 2008; Esarey 2016). $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

In equation (2), $Y_{i,j}$ represents a measure of solid fuel use (self-reported or weighed); *PERIOD* is an indicator variable that equals one for data collected during the end-line survey, and zero for those collected during the baseline survey; $\beta_2$, $\beta_3$, and $\beta_4$—the coefficients on the indicator variables for each of the three treatment arms—represent the initial treatment effects in each treatment arm, relative to the control communities[22]; and $\beta_5$, $\beta_6$, and $\beta_7$—the coefficients on the interactions between *PERIOD* and the treatment arm indicators—represent our DID estimates of the impact of the intervention in the treatment communities. $\beta_1$ isolates the change among the controls over the course of the intervention.

As shown in table 5, the coefficient on the treatment indicators in column (1) is negative and statistically significant; thus, the intervention led to large immediate reductions in weighed fuelwood use. The DID estimate in column (1) is positive but not statistically significant; disaggregating by treatment arms in column (2) also yields positive but statistically insignificant estimates. In addition, the coefficient for *PERIOD* is also negative, which suggests an average downward time trend in solid-fuel use among control households over the course of the intervention. The consistently positive DID estimates hint at a *rebound*

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[22] If each of our study communities is systematically distinct in terms of fuel use, then these coefficients would also reflect these baseline community-level differences. In such a scenario, we would be unable to disentangle the immediate treatment effect from these underlying differences in the amount of solid-fuel used. Observed similarities in stove- and fuel-use patterns, as well as in time allocated to cooking and preparing fuelwood across treatment and control communities, however, suggests that this is not the case (see table 2).

**Table 6.** Time spent collecting or preparing solid fuels, hours per week.

| | (1) | | (2) | |
|---|---|---|---|---|
| VARIABLES | Time spent | Bootstrapped 90% CI | Time spent | Bootstrapped 90% CI |
| Period | 0.59$^{***}$ | (0.59, 0.59) | 0.59$^{***}$ | (0.59, 0.59) |
| | [0.00] | | [0.00] | |
| Treatment | −2.37$^{**}$ | (−3.59, −1.15) | | |
| | [0.02] | | | |
| Period × Treatment | 1.50$^{*}$ | (0.26, 2.73) | | |
| | [0.07] | | | |
| Low | | | −1.98 | (−4.27, 0.31) |
| | | | [0.14] | |
| Medium | | | −3.87$^{***}$ | (−6.18, −1.57) |
| | | | [0.02] | |
| High | | | −2.97$^{*}$ | (−5.32, −0.62) |
| | | | [0.06] | |
| Period × Low | | | 1.87$^{***}$ | (1.87, 1.87) |
| | | | [0.00] | |
| Period × Medium | | | 0.52 | (−2.98, 4.03) |
| | | | [0.70] | |
| Period × High | | | 1.75$^{*}$ | (0.12, 3.37) |
| | | | [0.09] | |
| Constant | 11.75$^{**}$ | (5.95, 17.54) | 12.15$^{***}$ | (8.52, 15.78) |
| | [0.02] | | [0.001] | |
| Household controls | Yes | | Yes | |
| Observations | 113 | | 113 | |
| R-squared | 0.38 | | 0.40 | |

Note: The dependent variable is reported number of hours spent collecting or preparing solid fuels every week. Columns (1) presents results for all households assigned to any of the three treatment arms; column (2) presents results for each of the three treatment arms separately. Household-level controls include: household size; monthly expenditure; access to private tap water; ownership of LPG stoves; ownership of electric stoves or rice cookers; and awareness of the existence of improved stoves or clean fuels. Pairs cluster-bootstrapped $p$-values shown in brackets and 90% confidence intervals shown in parentheses, with clustering at the village level (Cameron *et al* 2008, Esarey 2016). $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

in measured solid-fuel use among treatment households over the course of the intervention (i.e. the treatment effect observed at the outset of the intervention fades over time). Columns (3) and (4) report estimates obtained using data on self-reported solid-fuel use; the results are strikingly similar. In particular, the positive and statistically significant DID estimate for treatment-low households in column (4) is consistent with the rebound hypothesis.

### 4.5. Time spent collecting or preparing solid fuel for combustion

We again employ a DID approach to account for the immediate impact of the intervention on self-reported time spent collecting or preparing solid fuel. Our results are reported in table 6. We find that the intervention did reduce the amount of time households report collecting or preparing solid fuels at the outset, but that this effect had diminished by the study's end. These results are also consistent with the diminished impact over time of the intervention on use of solid fuels noted above.

## 5. Conclusion

Researchers and policymakers alike have struggled to ensure sustained use of a variety of household environmental, health, and energy technologies. Using data from Cambodia, we show that households' use of an improved cookstove is responsive to economic incentives. Households given incentives based on objective measures derived from stove-use monitors used the stoves more frequently and for longer periods of time than others. Economic incentives linked to use (e.g. carbon finance delivered in response to verified changes in behavior) may therefore be effective for spurring adoption of ICS technologies.

While the results were somewhat inconsistent and not always statistically distinguishable from zero, simple verification visits and household stove-use diary checks accompanied by incentives also appear to reduce the total amount of—as well as time spent collecting—solid fuel, suggesting that even relatively inexpensive monitoring approaches could enhance use of household technologies. Given the high relative cost of SUMs-based verification, these simpler approaches may prove cost-effective in resource-constrained contexts. That said, households in the treatment-low and treatment-medium communities do appear to have 'over-reported' stove use (perhaps to obtain use-based incentives), and more research is needed to understand the limits and potential problems with such verification procedures, whose ultimate success hinges on honest reporting of use.

Finally, our results point to the need to carefully consider how behavior responds to such incentives. Somewhat unexpectedly, we found that initial reductions in solid-fuel use—as well as in the fuel collection and preparation burden—fade somewhat over time. The ‘substitution effect’ associated with receiving a cleaner cooking technology may thus be partially offset by an ‘income effect.’ In other words, while households appear to initially respond to a cleaner technology’s reduced price by switching away from traditional alternatives, over time the reductions may be offset by increased cooking and fuel consumption (perhaps from preparing more food), in contrast to results from other settings (e.g. Bensch and Peters 2013, Brooks *et al* 2016). In line with this phenomenon, the tendency of households to ‘stack’ multiple energy technologies and fuels reflects their desire for more services (Ruiz-Mercado and Masera 2015). While we do not have objective use data related to the other technologies that comprise the full energy mix used by our sample households, our survey measures do confirm that stove stacking was prevalent. Over eighty percent of respondents reported using two or more stoves for cooking and heating during the end-line survey.

The success of incentive-based interventions depends on how they are designed, how incentives are delivered, and how they interact with personal or societal norms and motivations (Gneezy *et al* 2011). Policymakers must carefully consider these elements, particularly when designing interventions that aim to promote use of environmental health technologies, whose use is frequently over-reported (Thomas *et al* 2013). Absent a complete and sustained substitution to cleaner technologies, many of the anticipated benefits—for the environment, health and livelihoods—of these solutions may not fully materialize. This is perhaps especially true for health (Burnett *et al* 2014), but rebound effects that increase energy use may also offset emissions or fuel savings benefits (Gillingham *et al* 2016, Greening *et al* 2000). Thus, while our study yields promising preliminary evidence that incentives can increase use of beneficial technologies in low-income contexts, future research—conducted in alternative contexts, with larger sample sizes that enable detection of smaller effects, objective measurements for all household energy devices, and greater variation in the levels of incentives—is sorely needed to better understand their net effects on overall social and environmental well-being.

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