Energy performance of wood-burning cookstoves in Michoacan, Mexico

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Abstract

There have been few detailed assessments of the actual impacts of improved stove interventions in rural communities, although many improved stove projects have reported overall efficiencies from tests in simulated kitchens using water-boiling tests (WBTs). This paper presents an integrated energy evaluation of the Patsari cookstove, an efficient wood-burning cookstove developed in Mexico that has recently obtained international recognition, in comparison to traditional cookstoves in rural communities of Michoacán, Mexico. The evaluation uses three standard protocols: the WBT, which quantifies thermal efficiency and firepower; the controlled cooking test (CCT), which measures specific energy consumption associated with local cooking tasks, and the kitchen performance test (KPT), which evaluates the behavior of the stoves in field conditions and estimates fuel savings. The results showed that the WBT gave little indication of the overall performance of the stove in rural communities. Field testing in rural communities is of critical importance, therefore, in estimating the benefits of improved stoves. In the CCT for tortilla making, the main cooking task in Mexican rural households, Patsari stoves showed fuelwood savings ranging from 44% to 65% in relation to traditional open fires (n = 6; P < 0.05). These savings were similar in magnitude to the average energy savings from KPT before and after Patsari adoption of 67% (n = 23; P < 0.05) in rural households exclusively using fuelwood. Similar energy savings of 66% for fuelwood and 64% for LPG, respectively, were also observed in households using mixed fuels. With sound technical design, critical input from local users and proper dissemination strategies, therefore, improved stoves can significantly contribute to improvements in the quality of life of rural people with potential benefits to the surrounding environment.

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1. Introduction

Biomass represents between 50% and 90% of primary energy consumption in developing countries, and 12% and 15% of global primary energy consumption [1]. Three-quarters of the global biomass used for energy is consumed in developing countries, where 77% of the world’s population lives, mainly in rural areas and in poor urban zones for cooking, water heating, space heating, and thermal power generation in a large variety of small industries (i.e., brick making, pottery, and others). Approximately 27 million rural people in Mexico still use biomass for cooking [2], where fuelwood represents approximately 80% of energy used by rural households and 50% of total energy use in rural communities [3]. The most frequently used fuelwood technology remains the open fire. Unfortunately, people that use these technologies are exposed to emissions originating from inefficient combustion that are associated with serious adverse health...
effects, affecting mainly women and young children. Damage associated with smoke from open combustion results predominantly from acute respiratory infections, which cause nearly 1.2 million premature deaths annually among children less than 5 years of age [4,5]. In Mexico, making tortillas represents more than half of fuelwood consumption, and women spend between 2 and 4 h/day on this task in close proximity to the stove, breathing smoke. Women that have home industries making tortillas to sell, which can be up to 20% of women in some communities, may spend as many as 8 h/day in these conditions [6]. Fuelwood use also presents other problems due to the cost or to the time and effort required to collect it, and in rural Mexican communities people spend an average of 15–20% of their income purchasing fuelwood [7].

Approximately 18.7 million rural people rely exclusively on fuelwood for energy, with the remainder using it principally in combination with LPG (8.5 million). Recently, LPG penetration has increased, particularly in larger semi-urban centers, where income levels and technology penetration are higher and fuelwood resources are more limited. In rural areas, however, LPG is almost always used in combination with traditional energy sources where mixed users generally use fuelwood as their main fuel for tasks with higher energy output, and LPG as a secondary fuel for smaller tasks such as heating milk for breakfast. In these communities, LPG tends to be a supplementary rather than a substitute energy source, due to an inadequate distribution network, high fuel costs, and inadequate adaptation of LPG stoves to local cooking practices, giving rise to more marginal reductions in fuelwood consumption and indoor pollution. Although with economic development increased adoption of LPG might be expected, economic development may not directly translate to increased LPG usage as the kitchen has a low priority inside the family [8,9]. With fuelwood usage likely to continue in rural Mexican communities, at least in the coming decades, there is a critical need to introduce effective measures that reduce the burden of health effects as a result of exposure to fuelwood combustion byproducts.

For several decades, improved stoves have been promoted to reduce fuelwood use and to improve quality of life for rural people. Initial evaluations of these efforts were mixed on the effectiveness of both stove designs and dissemination programs [10,11]. Since health, GHG, and fuel-saving benefits of improved wood-burning stoves are related to increased efficiency, evaluation of energy performance is critical to developing more effective technologies. Measuring the energy performance of a wood-burning stove is deceptively difficult, however, as the tests should reflect the conditions under which the stove would be used in real households. While a standardized global test may seem at first desirable to compare across programs, in practice, since cooking and stove usage are quite different between different regions, and even more so at national and global levels, this has proved quite challenging.

There has been little systematic evaluation of fuel saving and energy implications during daily activities in real communities that have converted from a traditional to an improved stove. Likewise, multiple fuel usage, transitional stove adoption patterns, or the ways in which families make use of different technologies to fulfill their food-cooking requirements have rarely been incorporated. Since use of multiple fuels is a common step in the transition from traditional to improved stoves, in agreement with social theories of technology dissemination through populations, evaluating these stages is critical to understanding the impacts of the transition.

As part of a comprehensive program of stove evaluation and monitoring, which includes evaluation of reductions in health impacts, personal exposures, indoor air pollution concentrations, greenhouse gas emissions, and improved families’ life [12], this paper presents an energy performance evaluation of the “Patsari” multi-pot wood-burning cookstove. The “Patsari” project won the Ashden Health and Welfare prize for Sustainable Energy in June of 2006,1 and has been disseminated in Mexico through a multi-institutional program since 2003. To obtain a more comprehensive picture of the impact of the stove, we present an integrated analysis where laboratory thermal efficiency tests are compared to both controlled cooking tests (CCT) and kitchen performance tests (KPTs) in rural communities in a before and after intervention assessment.

2. Methodology

2.1. Description of stoves

2.1.1. Traditional stoves

Cooking in this region of Mexico is typically performed on open fires surrounded by three-stone fire (TSF) (Fig. 1) and open fires with U-shaped surrounds (U-type) (Fig. 2). The U-shaped surrounds are built by the users in many regions of Mexico and are typically made of mud or clay. Although to some extent they “enclose” the fire in a kind of combustion chamber, they do not possess a chimney and combustion is incomplete and uncontrolled, generating a great quantity of particles and gases that are emitted directly into the kitchen. In both cases the pot or the comal2 is placed on the three stones or the U-shaped surround and an open fire lit beneath it. The TSF thermal efficiency typically oscillates between 5% and 17% [13–15].

2.1.2. Patsari stove

GIRA3 and CIECO4 developed an efficient wood-burning cookstove called the “Patsari,” which in the

1http://www.ashdenawards.org/winners/gira
2A comal is a large metal or ceramic flat surface on which tortillas are cooked.
4Center for Ecosystems Research (CIECO), National Autonomous University of Mexico (UNAM), www.oikos.unam.mx.
Purhepecha language means “the one that keeps,” referring to the fact that the device “keeps” (takes care of) users’ health, environment, and economy. Patsari is an improved design of the Lorena-style cookstove \[12\]. Although there are multiple models, the Patsari stoves tested here were built using brick and cement, with integrated metal comals that are sealed with clay to avoid smoke leaks into the kitchen, and a chimney to vent smoke from the kitchen. The external dimensions of the stoves were 80 cm wide by 100 cm in length, with a height of 27 cm. The stove has a main combustion chamber 20 cm tall with a metal comal that is 52 cm in diameter, ideal for cooking tortillas. One model of Patsari have adicional a smaller chamber with a metal comal 35 cm in diameter, designed to hold pots and used to cook beans, soups and for other tasks like boiling water. Both have two secondary chambers (or furnaces) for small pots too (Fig. 3a and b). For the CCT an additional model with clay comal was tested to evaluate the effects of comal composition on tortilla cooking.

2.2. Stove performance tests

Three standard tests were used in this study based on recent modifications\(^5\) to approaches developed in the 1980s by VITA [16] and elaborated by Baldwin [17]: (a) the water boiling test (WBT), which measures the time and fuel needed to boil a certain quantity of water under controlled conditions. This tests was in principle intended at the design phase for relatively fast feedback on design modifications, and may not reflect conditions under which the stove is used for cooking in communities; (b) the CCT, which more appropriately measures fuel consumption associated with the performance of a specific cooking tasks, but is hard to compare across regions or food types; and (c) the KPT, which is designed to evaluate family fuelwood consumption under real usage conditions in local communities, but is more difficult to perform and requires more resources and cooperation of local users. Changes to earlier versions of the tests included some minor procedural changes, the introduction of a “standard cooking pot,” and the use of modern, but fairly inexpensive, measuring equipment.

The laboratory tests (WBT and CCT) were carried out in a simulated kitchen testing facility at GIRA’s laboratory in Patzcuaro Michoacan, Mexico, using fuels purchased locally. All Patsari and open fire test iterations were performed by the same person and used oak fuelwood, air dried at ambient temperature. The field tests (KPT) were carried out in two rural communities of the Meseta Purhepecha of the state of Michoacan, Mexico.

2.2.1. Water boiling test

The WBT has three components: a test at high power that is conducted with both cold and warm start conditions and a test at low-power to simulate slow cooking tasks or task that require low heat. The tests were modified to accommodate multi-pot stoves, with three repetitions of each phase of the test for each fire/stove type. In the high-power cold start, the test begins with the stove at room temperature and uses a pre-weighed bundle of wood to boil 3 L of water in a standard pot. In the high-power warm start, a fire is reset immediately after the WBT cold start phase and the test repeated to identify differences in performance between a stove when it is cold and when it is warm. Lastly in the low-power simmering phase, a fire is reset using a pre-weighed bundle of wood after the high-power tests and used to simmer water \(3 \, ^\circ \mathrm{C} \) below boiling for 45 min.

The WBT assesses the thermal efficiency \(H\), the firepower \(P\), and the specific fuel consumption (SC) of the stove, where Thermal efficiency \(H\) is a ratio of the work done by heating and evaporating water to the energy

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\(^5\)Procedures, changes relative to earlier versions of tests, and analysis spreadsheets are available at \url{http://ceihd.berkeley.edu/heh.stove_perf_eval.htm}.
consumed by burning wood, mathematically,

$$H = \frac{4.186 W_w(T_f - T_i) + 2260 W_v}{f_d \times \text{LHV}},$$

where $W_w$ is the mass of water in the pot, the specific heat of water (4.186 J/g°C), and the change in water temperature ($T_f - T_i$), the product of the amount of water evaporated from the pot ($W_v$), and the latent heat of evaporation of water (2260 J/g). The dry-wood equivalent consumed during each phase of the test ($f_d$) and the LHV, lower heating value (also called net heating value).

Firepower ($P$) is a ratio of the wood energy consumed by the stove per unit time (in W) during each phase of the test, mathematically,

$$P = \frac{f_d \times \text{LHV}}{60(t_f - t_i)},$$

where $(t_f - t_i)$ is the duration of the specific test phase.

Specific fuel consumption ($SC$) is the ratio of the amount of fuelwood consumed to the amount of water remaining at the end of the trial, can be defined for any number of cooking tasks, and should be considered “the fuelwood required to produce a unit output” whether the output is boiled water, cooked beans, tortillas, or loaves of bread. In this case specific fuel consumption refers to a measure of the amount of wood required to produce 1 L (or kilo) of boiling water, mathematically,

$$SC = \frac{f_d}{W_{wf}},$$

where $W_{wf}$ is the mass of water boiled.

2.2.2. Controlled cooking test

The CCT is a test designed to evaluate stove performance as a woman from a local community conducts specific local cooking tasks and provides a range of performance metrics that may be used to evaluate different designs of stoves including fuel consumption (SC), residual charcoal, quantity of food cooked, and time used in the task. While this test gives a good indication of stove performance in local communities, it is hard to compare stove performance across communities and stove types. Mathematically, SC is expressed (on a dry basis) as

$$SC = \frac{f_d - [C_h(H_{ofw}/H_{och})]}{1 \text{ kgTortillas}},$$

where $C_h$ is the amount of residual charcoal resulting from the combustion of fuelwood; $H_{ofw}$ the enthalpy of fuelwood (20 MJ/kg); and $H_{och}$ the enthalpy of charcoal (28 MJ/kg).

Cooking of handmade corn tortillas was evaluated in the CCT as this activity is one of the most important in the life of rural families in México and one of the major energy demands [6,7]. A woman from a nearby community cooked 1 kg of tortillas each time in the different stoves, using
traditional methods. The test was repeated six times for each fire/stove type using TSF, U-type fires, and Patsari stoves with both metal and clay comals. Measurements also included the moisture content of fuelwood, ambient temperature, time needed to cook the dish, and time to light the fire in the case of fuelwood.

2.2.3. Kitchen performance test

The KPT is a field-based test, designed to evaluate actual stove performance under conditions in local communities, in which daily fuel use and coking tasks are monitored in community households over a specified time frame, usually 1 week. In the central Mexican highlands in the state of Michoacan, 15 municipalities were selected where reliance on biomass fuels for primary energy provision was over 80% [12]. From these municipalities 600 households were randomly selected in six Purepecha communities for participation in a case-control assessment of the effects of the improved Patsari stove on respiratory health effects [18]. For KPT, 23 households exclusively using fuelwood were selected randomly from the cases in the health study in two communities of the Meseta Purrhepcha: Comachuen and La Mohonera. From the same communities 14 households that used a combination of fuelwood and LPG. In all households oak and pine were main fuelwoods used.

The KPT was a longitudinal evaluation of energy consumption to control for between household variability. While a pilot study suggested that smaller samples were sufficient for statistically significant differences in per capita energy consumption, oversampling of open fire stoves was conducted in the initial phase, to account for drop out due to migration, lack of wood availability, and other factors. Sample numbers were reduced in subsequent phases due to resource limitations in following all households through all three phases. Results do not represent reductions in per capita community or population energy consumptions, therefore, but are indicative of users of the stove. The KPT was performed in three phases: (a) Phase 1, as a baseline when the family used an open fire or open fire in a traditional U-shaped stove (dry season), with 43 households (53% exclusive fuelwood users and 47% mixed users); (b) Phase 2, an intermediate phase 6 months after installation of the improved Patsari stove (rainy season), with 32 households (66% exclusive and 34% mixed); and (c) Phase 3, after 1 year of use, with 14 households (57% exclusive and 43% mixed users) (Table 1).

The daily consumption of LPG and fuelwood used by each family was monitored over a 7-day period, before and after the introduction of Patsari cookstove. In addition, the number of people for whom food was prepared at each meal was recorded, differentiated by sex and age. To obtain fuel consumption per capita, an equivalence factor called a standard adult7 was used, which relates the fractional food requirement (and energy needed to cook the food) for a child, woman, or elderly person to that of an adult man of reproductive age. Fuelwood was not provided to families to minimize bias in family fuel consumption. In Phases 2 and 3, it was common that some families used Patsaris and traditional cookstoves combined.

3. Results

3.1. Water boiling test

Table 2 shows results of WBT performed for each stove type. The U-type open fire and the TSF had relatively consistent thermal efficiencies in the three test phases from 13% to 19%, which were in relatively good agreement with reported efficiencies [13–15]. In the low-power phase, however, specific fuel consumption was much greater for the open fires and U-shaped stoves than in the high-power phases, although there was large variability in the measurements. The Patsari, however, demonstrated much lower efficiencies (7%) in the high-power cold start and somewhat

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7Standard adult equivalence factors defined in terms of sex and age: child: 0–14 years, 0.5; female: over 14 years, 0.8; male: 15–59 years, 1.0; male: over 59 years, 0.8. (Guidelines for Woodfuel Surveys, for FAO by Keith Openshaw).
lower efficiencies in the high-power warm start (17%) compared to the low-power phases (30%). In addition, the Patsari showed much lower specific fuel consumption in the low-power phase relative to the high-power cold start.

The power of the devices varied between 6.4 kW (U-type) and 9 kW (TSF and Patsari) for the cold start phase, and among 4.4 kW (Patsari) and 8.1 kW (U-type) for the hot start. While the firepower in the cold start phases was similar for Patsari and TSF with much lower thermal efficiency for the Patsari, in the warm start phase the thermal efficiencies were similar, but the firepower for the Patsari stove was much lower than the open fire and U-shaped stove (Fig. 4).

3.2. Controlled cooking test

Table 3 and Fig. 5 shows fuelwood and energy consumption in six repeat CCT of tortillas performed for each stove type. Patsari stoves showed a considerably lower fuelwood and energy consumption compared to TSF and U-shaped stoves. The single entrance Patsari stove with metal comal showed the lowest fuel consumption for making tortillas (0.64 ± 0.07 fuelwood kg/tortilla kg), followed by the clay comal Patsari, the TSF, and the U-type. The savings achieved by the Patsari were 55% and 65% in comparison with the U-type, and 44% and 57% compared with the TSF, and were statistically significant at 95% confidence level.

3.3. Kitchen performance test

Table 1 shows characteristics of households that participated in the KPT. Average household size (measured in standard adults) ranged from 4.2 to 5.2 members. The sample size decreased from Phases 1 to 3 due to participant dropouts, migration, lack of availability of fuelwood when...
In a few instances mixed users stopped using LPG in Phases 2 and 3.

3.3.1. Phase 1: traditional stove user’s measurement

In this phase, there were no significant differences between participating households in the two study communities ($n = 23$, exclusive; $n = 20$, mixed; Student’s $p > 0.05$). In contrast, as shown in Fig. 6, exclusive fuelwood users showed significantly higher fuelwood consumption relative to mixed users of fuelwood and LPG (Student’s $p < 0.05$). Average per capita fuelwood consumption was $3.4 \pm 0.8$ kg/cap/day (equivalent to $54.1$ MJ/cap/day) for exclusive users and $2.3 \pm 1.1$ kg/cap/day ($41.8$ MJ/cap/day) for mixed users, respectively. Mixed users had, in addition, an average per capita daily consumption of LPG of $0.09$ kg ($4.84$ MJ/cap/day).

3.3.2. Phase 2: measurement after 6 months using Patsari stove

The second phase was carried out in the rainy season; as discussed above some families still used the traditional stove and others were using the Patsari stove regularly. Table 4 shows the comparison between Phases 1 and 2 for those households that were available for the test and were also already using the Patsari stove (alone or in combination with traditional cookstoves). Significant fuel and energy savings were obtained with regard to the traditional cookstoves. Exclusive Patsari users showed $57\%$ savings compared to their previous consumption using traditional cookstoves. Mixed users saved $48\%$ on fuelwood and $30\%$ on LPG, for an aggregate $46\%$ savings in energy use. Similar savings were obtained when restricted to paired analysis.

3.3.3. Phase 3: measurement after 1 year using the Patsari stove

Table 5 shows fuelwood and energy consumption a year after the introduction of the Patsari stove, and energy savings relative to open fires or U-shaped stoves. Exclusive fuelwood users consumed $1.1$ kg/cap/day of fuelwood while mixed users consumed $0.8$ kg/cap/day. Savings in fuel and energy consumption for those using wood-burning efficient cookstoves were $67\%$ for exclusive users and $66\%$ for mixed users. The latter use LPG to cover $12\%$ of their energy needs for cooking and consumption declined to only $0.03$ kg/cap/day, representing a savings of more than $60\%$. Similar savings were obtained for exclusive users when restricted to paired analysis, but were slightly lower for LPG ($51\%$).

4. Discussion

There has been little formal in-field evaluation of the effectiveness of improved stoves as an intervention, as it is both challenging and complex to measure the degree to which new improved stove technologies improve conditions in rural households, through replacing traditional methods. It is not only challenging to recruit statistically representative study participants in areas where individual behaviors in cooking activities and housing conditions vary widely as a result of non-standardized construction norms, but also resource intensive to keep sampling equipment and personnel in the field to follow households over time, relying on goodwill of communities for participation.

As a result of these difficulties, most stove projects resort to laboratory-based WBTs that assess the thermal efficiency of the stove as an indicator of stove performance and fuel saving, which has a tendency to be used as an absolute metric of the value of the improved stove. Efficiency by itself is not a good indicator, however, and although fuel consumption provides more information [19], the $67\%$ savings found in the KPT demonstrate that...
laboratory tests are not enough and in-field evaluations of performance in rural communities are essential. Although challenging in approach, this study demonstrates, therefore, the utility of an integrated approach to testing stove performance in rural communities in which results from the two laboratory tests (WBT, CCT) are used to inform on in-field evaluations of stove performance in the KPT.

4.1. Reductions in energy use and multiple fuel usage

Many families used both the traditional stove in combination with the Patsari, especially for high-power tasks such as heating water for bathing, making nixtamal, and heating the home during cold periods. In spite of the continued use of open fires for some tasks, the reductions in fuelwood and per capita energy consumption represent considerable fuel savings in these households (67%). Clearly, on a community or population basis per capita reductions for the whole community would be expected to be lower, depending on the degree of stove adoption and use, and the reductions here are indicative of reductions in households using the stoves.

Similarly, although LPG stoves were present in a large fraction of the rural households in these communities, these households continued to use the traditional open fire stoves, rather the LPG stove tends to be used for specific cooking tasks (usually heating water for tea, or short cooking or reheating tasks). While LPG stoves have been

### Table 4

<table>
<thead>
<tr>
<th>Type of users</th>
<th>Traditional cookstove (before)</th>
<th>Patsari (after)</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kgfw/cap/day</td>
<td>MJ/cap/day</td>
<td>kgfw/cap/day</td>
</tr>
<tr>
<td>Exclusive</td>
<td>3.4±0.8</td>
<td>54.1±13.0</td>
<td>1.4±0.6</td>
</tr>
<tr>
<td>Mixed</td>
<td>2.3±1.1</td>
<td>41.8±17.5</td>
<td>1.2±0.8</td>
</tr>
</tbody>
</table>

Average daily fuel and energy consumed per standard adult in homes with traditional stoves and in homes after 6 months of Patsari usage (±SD).

### Table 5

<table>
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<tr>
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<td>3.4±0.8</td>
<td>54.1±13.0</td>
<td>1.1±0.4</td>
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<tr>
<td>Mixed</td>
<td>2.3±1.1</td>
<td>41.8±17.5</td>
<td>0.8±0.3</td>
</tr>
</tbody>
</table>

Average daily fuel and energy consumed per standard adult in homes with traditional stoves and in homes after 1 year of Patsari usage (±SD).

Fig. 6. Kitchen performance test. Fuelwood ($F_w$) used in the baseline by type of user.
widely promoted as options to achieve significant health benefits in rural communities, in practice these benefits are not fully realized due to the continued presence of very polluting open fires in the same room. Fig. 7 demonstrates through per capita energy consumption how an integrated strategy for multiple stove promotion based on specific local cooking requirements can achieve greater benefits to these communities. Reflecting current promotion of LPG stoves in communities, per capita energy consumption in households in which LPG stoves were present was 24% less than traditional open fire stoves. On the other hand, after installation of the Patsari stove per capita energy consumption was 67% less than the traditional open fire stoves, and even reached 74% in households where LPG was also present. Policies directed at the dissemination of only LPG will therefore result in much smaller energy reductions—and virtually no health gains—than an integrated strategy where improved wood-burning stoves are combined with strategies for gradually shifting to LPG on specific cooking tasks. These last strategies will also reach a much wider social basis and result in larger health, environmental, and GHG emission benefits. Clearly, these integrated strategies could also include multiple wood-burning stoves targeted at specific local cooking needs, such as inclusion of secondary high-power improved stoves for water heating for bathing, or similar tasks.

The KPT was originally designed to accommodate only one fuel. While in some parts of the world households still rely on only one fuel for cooking, use of more than one fuel and multiple stoves is probably the most common case. Since introduction of an improved stove would be expected to impact total household energy consumption across all stoves and fuels, assessment of the overall impact in real households was required to provide robust data on the effectiveness of the stove. The KPT protocols were adapted, therefore, to deal with multiple stoves and fuels and results are presented in terms of total energy consumption and energy savings, in addition to the masses of individual fuels used or savings reported by previous stove projects. In addition, in this study users of the improved stove that used mixed fuels and those that exclusively used fuelwood have been differentiated to illustrate the potential bias in estimates that may result from not accounting for other energy sources. For these communities in Mexico, therefore, not only would overall energy use be underestimated through not assessing the LPG consumption, but the energy savings in LPG use that result from installation of the improved stove would not be credited to the performance of the improved stove. This is of considerable importance in estimation of greenhouse benefits and potential carbon credits that may accrue to defray the cost of the improved stove, in addition to the financial benefits of reduced LPG consumption to the household.

4.2. High-power vs. low-power

The Patsari stove demonstrated low thermal efficiencies for tasks that require high-power, performing less well than traditional stoves, a situation found in other studies [20,21]. Studies on the Lorena stove in Michoacan by Masera [6] showed similar consumption and savings (13.83 MJ/kg) in relation to the TSF (29.21 MJ/kg). The results of the high-power phases of the WBT, however, were not indicative of the actual performance in households in the field in the KPT, or with results of the CCT, which indicated that the
stove was efficient for local cooking practices and capable of achieving significant fuel savings.

Thermal efficiency of the Patsari stove averaged 17% in high-power and up to 30% in low-power phases. Thermal efficiencies of the “Plancha” stove from Guatemala showed a similar pattern where efficiencies in the high-power phase of the WBT (9%) were considerably lower than those in the low-power phase (16%) [20,21]. The magnitude of the difference, however, was much greater for the Patsari, although both improved stoves, the Plancha and the Patsari, are Lorena-style stoves and built with similar materials (bricks, clay, and sand). The differences in thermal efficiency are probably the result of improved combustion chambers in the design of the Patsari, which appear to improve operational conditions such that fuel savings in the field are greater than 60% and are comparable to 50–75% reported by Ayoub [13] for a metallic stove.

In these communities in Mexico cooking accounts for the bulk of fuelwood consumption (usually from 80% to 95%), with tortilla making accounting for 43% of total fuelwood use (57% including the preparation of the tortilla mix—nixtamil), for which the average family in Cheranatzicurin and Jaracuaro villages needs more than 4 kg of fuelwood daily [6]. The second most energy intensive task is the preparation of beans, which are first cleaned, washed, and simmered for 3.5–4 h in a ceramic pot, during which water is frequently added. Since these low-power tasks account for so much of the fuelwood and energy requirements for cooking, it is perhaps not surprising that, in the WBT, the low power simmering phase was a better indicator of fuel efficiency in the field compared to the high-power WBTs, which showed no relationship to actual fuel savings estimated by the KPT. This raises fundamental questions about the utility of the high-power WBTs as indicators of stove performance in communities. Perhaps more importantly it suggests that stoves that have been promoted on the basis of fuel savings demonstrated by laboratory WBTs are likely not realizing these savings in practice. In a similar manner, many greenhouse gas and air pollution emissions estimates that are also based on laboratory WBTs also do not represent the situation in real communities [22]. At a minimum, more emphasis should be placed on the low-power phase of the test unless it is demonstrated that specific local cooking in households derives the majority of energy consumption from high-power cooking tasks. Although measurement of exact quantities of wood used for each cooking task would be very invasive to residents of the households during a KPT, in future stove performance studies CCTs on common cooking tasks could be performed to determine the proportion of cooking tasks using high-power to the proportion using low-power as a prelude to using the WBT. Of course, the KPT would be better suited to assess the effectiveness of the stove in achieving fuelwood savings, but the CCT may aid designers in interpreting the results of the WBT in the design phase.

4.3. Cold start vs. hot start

The WBT includes both cold start and hot start phases. The relevance of each phase, however, is also dependent on cooking practices in local communities. In many households in these communities the fire is lit around 5 a.m. in the morning and will remain warm through most of the day, although perhaps not as warm as in the second phase of the WBT when the stove was lit very recently. Although the thermal efficiencies of the high-power warm start phase are likely to be more representative of the majority of daily activities, therefore, this phase was still not indicative of the fuel savings demonstrated by the low-power phase WBT and the KPT. Thermal efficiencies for Patsarís, TSF, and U-type stoves were quite similar during this phase.

4.4. Length of KPT

Performing a KPT is both time- and resource-intensive, and often the reason given for selecting less informative stove performance tests (SPTs) [19]. Conducting the KPT on a longitudinal basis, however, remains the only current test that evaluates energy performance of the stove in communities. Further, since few reported studies in the literature have extensively performed the KPT, a continuing issue is what the optimal sampling time would be for the KPT that minimizes impact on participants (and expense and effort required for conducting the KPT), while achieving maximum benefit in reduction of variability between and within households. This is not only important for sample size calculations in reducing the number of households that are needed to show statistically significant differences, but also important in reducing potential sampling bias in estimating the energy performance of the improved stove. Minimizing the impact on participants also increases the likelihood of participant retention in the study, which also has resource implications in reducing the over sampling necessary in the initial stages.

With little data with which to evaluate the optimal period to perform the KPT, the current study conducted the KPT on a daily basis for a 7-day period, determined primarily to cover a weeks activities rather that from statistical rationales. As a result of the daily measurements, the utility of the KPT sampling time in collecting representative data can be evaluated, especially given the decline in study participation over the 1-year period. Fig. 8 shows the cumulative average fuel consumption for exclusive users of open fires over successive 24-h periods. The coefficient of variation reduced from 0.54 to 0.24 by the end of the sampling period. By the fourth day, 84% of the reduction in the coefficient of variation had occurred and the average fuel consumption was 3.51 compared to the average at the end of the sampling period of 3.39. Thus, if the KPT was performed for 4 days instead of the full sampling period a maximum potential bias of 3.5% in average fuel consumption estimates might be incurred, with a corresponding increase of 5% in the coefficient of
variation. Using the coefficients of variation here, this increase of 5% would imply an approximate increase of six households to observe 20% difference in mean fuel consumption.

In general, there were no significant differences in energy consumed per capita between weekdays and weekends. In a few cases the consumption of energy in the home increased on the weekend as the husband or children usually worked or studied away from home and returned during the weekend. Conversely, in rare cases the family was outside the home on Saturday or Sunday and did not cook, but within the households measured here no differences were observed. While other areas may differ therefore, in this area, choosing 4 days for a KPT irrespective of day of the week would give a good approximation of energy consumption. Clearly seasonal differences are important, however, and resources would be better spent on measuring on multiple occasions if annual average energy consumption was desired. For a before and after longitudinal study, measurements should occur after a year of use, or at least in the same season, to avoid these seasonal differences and bias in estimates. Unfortunately, this has significant resource implications for performing stove effectiveness tests as participant drop out rates as a result of migration, absence for work, and lack of willingness tend to increase over the longer time frame, necessitating an increased sample size to account for these losses. Even greater increases in sample size would be required, however, if a cross-sectional design was used due to considerable between-home variability, although the homes could be sampled concurrently, resulting in a study that could be completed in a shorter time frame.

5. Conclusions

The Patsari stove offers clear benefits with respect to traditional stoves, with an average reduction in energy consumption of 67% in households exclusively using fuelwood. Average reduction in energy consumption reached 66% for fuelwood and 64% for LPG in households using mixed fuels, and fuelwood savings ranged from 44% to 65% in the CCT for tortilla making, the main cooking task in Mexican rural households.

Methodologically, our study shows that the high-power phases of the WBT were not indicative of the fuel consumption in rural communities. Although the low-power phase of the WBT was more indicative, it still underestimated the fuel savings in rural communities. Field testing in rural communities, such as the KPT, is of critical importance, therefore, in estimating the benefits of improved stoves. Although laboratory testing using simulated cooking activities has been developed as a metric to compare stoves across regions, it is of questionable benefit in estimating the real fuel saving of the stove. While it is useful in the design phase, the interpretation of WBT results should be combined with CCT testing of the relative importance of high- and low-power cooking phases in local cooking activities. Ideally, the KPT should be reduced in length to 4 days of assessment and performed during the same season in before and after interventions in these communities, to reduce participant impact. Finally, the decrease in the use of other secondary fuels like LPG when an improved fuelwood stove was introduced confirms that total household energy consumption across all stoves and fuels should be assessed to provide robust data on the effectiveness of the stove.

Since success of an improved stove program ultimately is defined by the numbers of stoves in actual usage in communities, rather than simply the number of stoves that are disseminated and built, stove performance should be evaluated from multiple perspectives and not solely on thermal efficiency or fuel consumption. In particular, both stove performance and acceptance by local communities should be incorporated in the evaluation.
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