An Evaluation of Household Energy Systems in the Himalayan Region

by

Lisa Tang

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Author . . . .
Department of Mechanical Engineering
May 6, 2022

Certified by . . . .
Daniel Frey
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Nicolas Hadjiconstantinou
Graduate Officer

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Abstract

Biomass cookstoves are prevalent in rural areas in developing countries around the world. The smoke from biomass burning results in high levels of household air pollution, which cause respiratory and pulmonary diseases. While many improved stoves have been developed to increase cooking efficiency and reduce household air pollution levels, the Himalayan region presents unique implementation challenges in its remoteness and the high space heating needs faced by households. In order to characterize the performance of existing Himalayan stoves, a handmade two-pot clay stove based on traditional north Indian stoves was constructed and tested in D-Lab with the Water Boiling Test. The stove's efficiency was found to be between 13 and 16%. The addition of a grate did not significantly change stove performance, and the addition of pot stands concentrated more cooking power on the front cooking vessel but did not improve overall thermal efficiency. The results from field visits to north India and Nepal in January 2022 are also presented. The cooking efficiencies of stoves in the field ranged from 4 to 13%, and stove thermal efficiencies were found to negatively correlate with fuel use and test duration. Households' ambient indoor temperatures and pollution levels increased when their biomass cookstoves were fired. Ambient particulate matter levels in the field were found to be two to three orders of magnitude above World Health Organization standards, and average indoor temperatures were below the accepted standard. Chimneys approximately halved pollution levels, but did not remove all pollution from households. Pollution levels within a household were found to increase with colder weather, due to space heating needs being met with increased operation of biomass stoves. Due to the strong connections between cooking and heating in the Himalayan region, a new methodology is proposed for the holistic evaluation of household energy for communities which use biomass stoves.

Thesis Supervisor: Daniel Frey
Title: Professor of Mechanical Engineering

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Contents

List of Figures

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List of Tables

Chapter 1

Introduction

Biomass-fueled cookstoves are used by 2.6 billion people in rural communities around the world [1]. The high levels of household air pollution from these stoves cause respiratory and cardiac ailments that result in the annual deaths of 4 million people [2]. In addition to the impact on human health, cookstove emissions and deforestation from fuelwood gathering contribute to climate change [1], [3].

Many decades of work have been dedicated to developing improved cookstoves with better stove performance and reduced levels of pollutant emissions. In 2017, MIT D-Lab began a research project focused on improving household energy outcomes and reducing household air pollution in the Himalayan region. The Himalaya provide unique challenges for implementing clean cooking solutions. The remoteness of the region makes it difficult to establish supply chains for improved stove technologies and cooking fuels. In winter, many rural communities also use their cookstoves for space heating, and existing improved cookstove designs often do not account for the heating needs of colder, high-altitude regions. D-Lab's Himalayan Home Energy Project takes a variety of research approaches, including community surveys and field data collection, laboratory testing of stoves, and computational simulations of combustion in cookstoves. To provide the necessary local connections for the project, D-Lab is working closely with universities, social organizations, stove manufacturers, and rural communities in north India and Nepal.

This thesis presents results from laboratory and field evaluations of Himalayan cookstoves and household energy systems. In order to obtain quantitative performance metrics of traditional clay stoves found in the Himalayan region, laboratory tests were conducted in D-Lab on a handmade model stove. These tests assessed stoves' cooking power, thermal efficiency, internal and surface temperatures, and the resulting pollution levels when the stove was fired. The effects of different species and drying methods of firewood and minor changes to the stove design were also investigated. In January 2022, the team conducted a field visit to India and Nepal in order to better understand the cookstove designs and household energy systems found in rural communities. Data were collected on households' ambient temperatures and ambient pollution levels, and tests were also conducted to determine the performance of cookstoves in the field. In addition, the D-Lab team performed surveys to assess communities' practices and attitudes regarding cooking and heating.

Many existing evaluation standards for cookstoves do not account for the stoves' secondary purpose of space heating in colder climates. This thesis concludes with a proposed methodology for the evaluation of dual-use biomass stoves and household energy as a whole in rural settings. In addition to cookstove performance, the methodology includes parameters such as the thermal responses of stoves and thermal masses, and heat loss from the home through conduction and air infiltration. When implemented, the methodology will allow researchers to model energy flow through households and predict the effects of changes to stove designs and other parameters of the household energy system.

Chapter 2

Background

2.1 Biomass Stoves and Household Air Pollution

2.6 billion people around the world cook with biomass stoves [1], most of whom reside in rural areas in developing countries [2]. These stoves have a wide range of designs, including simple open fires and enclosed stoves built with clay or sheet metal. The biomass used for fuel is most often firewood, but agricultural waste or animal dung are also common fuels.

When biomass is burned incompletely, it releases harmful pollutants into households, including carbon monoxide, nitrogen and sulfur oxides, and particulate matter [4]. These pollutants contribute to household air pollution (HAP), which has a severe impact on human health. Over time, HAP can lead to respiratory and pulmonary diseases, including pneumonia, chronic obstructive pulmonary disease, stroke, heart disease, and lung cancer. HAP has also been linked to eye diseases and cataracts [2], [4]. Annually, there are nearly 4 million deaths that can be attributed to household air pollution [2].

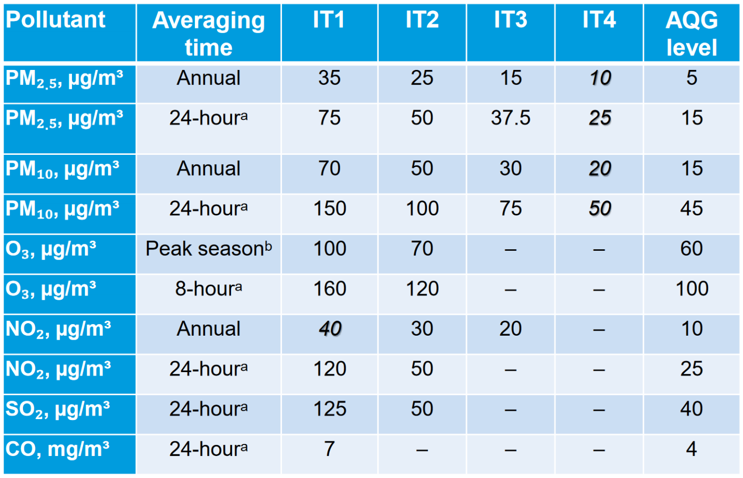
These health effects disproportionately impact women, who often cook for the household, and young children who remain in the home [2], [4]. The collection of firewood can also be time-consuming, dangerous, and physically taxing, and cooking on simple biomass stoves can cause burns and other injuries [1], [2].

In addition to its effect on human health, biomass-burning stoves have a significant impact on the climate. These stoves generate over one billion tons of carbon dioxide annually, accounting for 3% of human-caused climate change and 25% of global emissions of black carbon [1]. Unsustainable wood harvesting practices can also lead to deforestation, causing further anthropogenic climate forcing [3].

More than 50 million people live in the Himalayan region, where many rural communities primarily use biomass fuels for cooking and space heating [5]. Cooking makes up 37% of fuelwood energy needs in the Indian Himalaya, and 73% of rural families in the Indian Himalaya mainly use biomass fuels for household energy [3]. Similarly, two-thirds of households in Nepal mainly use biomass fuels for cooking [6], and traditional energy resources such as firewood, agricultural residue, and animal dung make up 68% of Nepalese energy use [7]. Population growth and deforestation in the Himalaya are reducing the availability of firewood; as a result, firewood collection is growing more time-consuming in some areas, which can exacerbate poverty [3].

The high altitudes and cold winters of the Himalaya lead households to burn more biomass for space heating, increasing fuel use and household air pollution levels. In rural Himalayan communities, indoor temperatures are often below 10°C in winter [5]. In the Indian Himalaya, space heating makes up 19% of average annual fuelwood energy needs [3]. Studies have found that wood use varies between 1 to 3 kg per capita per day in the rural Himalaya; much of this variation is seasonal, with wood use doubling or tripling in winter [6]–[8]. Cooking and heating in the Himalaya are often connected, as the same biomass stove is frequently used for both purposes [3].

25% of deaths associated with household air pollution occur in South and Southeast Asia [9]. Within India, health issues from HAP disproportionately impact the states of northern India, where higher percentages of the population use solid fuels [10]. Measurements made by previous D-Lab studies in the state of Uttarakhand in northern India shows average PM 2.5 levels near 2500 $\mu g/m^3$ and average PM 10 levels near 6000 $\mu g/m^3$ [5]. These levels are two orders of magnitude times higher than the World Health Organization's air quality guidelines. The WHO's interim and final target levels for indoor air pollutants are shown in Figure 2-1 [11].



Pollutant	Averaging time	IT1	IT2	IT3	IT4	AQG level
$PM_{2.5}$, µg/m^3	Annual	35	25	15	***10***	5
$PM_{2.5}$, µg/m^3	24-hour[a]	75	50	37.5	***25***	15
PM_{10}, µg/m^3	Annual	70	50	30	***20***	15
PM_{10}, µg/m^3	24-hour[a]	150	100	75	***50***	45
O_3, µg/m^3	Peak season[b]	100	70	–	–	60
O_3, µg/m^3	8-hour[a]	160	120	–	–	100
NO_2, µg/m^3	Annual	***40***	30	20	–	10
NO_2, µg/m^3	24-hour[a]	120	50	–	–	25
SO_2, µg/m^3	24-hour[a]	125	50	–	–	40
CO, mg/m^3	24-hour[a]	7	–	–	–	4

Figure 2-1: The World Health Organization's interim and final target levels for various household pollutants [11].

Various government programs in India and Nepal promote transitions away from biomass fuels and traditional stoves. The Nepalese government provides government subsidies for biogas and improved cookstoves, and is also encouraging solar power and small-scale hydropower [7]. There are also initiatives to expand grid connections in India, but the high cost and lack of reliability of electricity remain issues and discourage its use for important household energy functions such as heating and cooking in the Himalaya [3], [7].

Some government initiatives in India have specifically focused on clean cooking. The National Program for Improved Chulhas (NPIC) in India ran from 1984 to 2002, with the goal of developing and promoting improved biomass cookstoves. The NPIC distributed subsidized improved cookstoves to households across India, and provided financial and educational support to start clean cooking-related small businesses [12]. The program also developed an extensive catalogue of improved stoves, with test results focused on improving thermal efficiency and reducing pollution [13].

Even with government funding and external support, there are still many barriers to the implementation of clean cooking technologies in South Asia and the Himalaya. The NPIC program reached 33 million households in India, but little data exists on whether households given subsidized improved stoves have continued using them [12]. The 2016 Pradhan Mantri Ujjwala Yojana (PMUY) program in India provided subsidized LPG connections to tens of millions of poor households, but studies also did not find evidence of consistent usage [14].

The barriers to adoption for improved cooking technologies are partially economic. Rural households can often gather biomass fuels and construct traditional stoves for free, and high costs and unreliable supply chains can dissuade households from using improved stoves and fuels. New technologies also often fail to be adopted due to their incompatibility with cultural preferences, such as the taste or type of food or additional uses of traditional stoves beyond cooking [15]–[17]. The ease of stoves' construction and use are also important to users, and stoves that are difficult to operate and maintain are less likely to be widely adopted [12]]. Households sometimes modify improved cookstoves to suit their needs, which reduces their effectiveness [16], [18]. The Himalayan region provides unique challenges to implementing clean cooking technologies. The remoteness of mountain villages makes it more difficult for households to access improved cookstoves and non-gathered fuels. In addition, the need for space heating in colder weather encourages the increased use of biomass-burning stoves.

Stove stacking, where households with improved stoves continue to also use traditional stoves, is a common practice in rural communities in South Asia and the Himalayan region. Stove stacking drastically reduces the benefits of improved stoves, as negative health effects are caused by even short term exposures to household air pollution [1]. Surveys in Punjab found 73% of households had mixed fuel use [19], and a study in Himachal Pradesh found that 90% of households used wood for cooking and heating despite widespread ownership of liquefied petroleum gas (LPG) stoves [20]. A majority of Nepalese households use a mix of traditional and improved fuels, and 80% of mixed-fuel-use households only occasionally use improved fuels [7]. The phenomenon occurs due to the high costs of improved fuels, as well as traditional stoves being better suited to certain foods and cooking processes. Stove stacking can also be seasonal, since firewood stoves may be required to meet space heating needs in the winter [20], [21].

Despite these challenges, studies have uncovered effective ways to encourage the dissemination of improved cookstoves. Providing education and training to stoves' intended users can increase rates of adoption, and local manufacturers and salespeople play important roles in promoting improved stoves [15], [16], [18], [22]. During development of clean cooking solutions, it is crucial for external organizations to work in conjunction with local people and seek regular feedback from the community [23], [24].

2.2 Overview of Improved Cookstove Technologies

As wood is heated to 300°C and fed with a constant supply of oxygen, it burns and releases heat and volatile gases. When these volatile gases are mixed with additional oxygen at higher temperatures of 550°C, they burn again, releasing heat; the burning of the volatile gases raise the fire temperature above 1100°C and make up two-thirds of the energy released during combustion. This secondary combustion of the volatile gases is needed for cleaner combustion; if there is insufficient oxygen, unburned gases exit the stove as smoke, which contains pollutants such as particulate matter, carbon monoxide, carbon dioxide, nitrous oxides, and sulfur oxides [25].

Char remains after all of the firewood's volatile gases are released. The carbon-based char layer can continue to react with oxygen and burn, forming carbon monoxide and ash. If there is sufficient air, the carbon monoxide further reacts with oxygen to form carbon dioxide. Burning char at the bottom of a stove can serve as a heat and ignition source for fresh fuel. However, char and ash have lower thermal conductivity compared to firewood, and they can also limit heat transfer within the stove, slowing the combustion process [25].

A cookstove's thermal efficiency is defined as the percentage of the energy contained within the fuel that enters the cooking pot. Previous studies report a wide variety of thermal efficiencies for traditional clay or mud stoves in South Asia, which range anywhere from 3 to 30% [26]–[28]. Most commonly, studies report traditional clay stoves' efficiencies to be between 5 and 15% [13], [29]–[31].

Many decades of work have been conducted on improving biomass cookstoves, generally through a combination of increasing the stove's thermal efficiency, which reduces the amount of fuel needed to complete a cooking task, and reducing the stove's emissions. This section provides a brief overview of existing improved cookstove designs and common practices for improving cookstove combustion performance.

2.2.1 Stove Design and Construction

In order for secondary combustion of volatile gases to occur and reduce the level of harmful pollutants, high fire temperatures and a sufficient oxygen supply are needed. As a result, an important stove design consideration is matching the air supplied to the cookstove to the air needed for combustion. Traditional cookstoves often have insufficient airflow due to ash, char, and unburned fuel blocking airflow into the stove. On the other hand, excessive airflow can lower the temperatures in the combustion zone, impeding the volatile gases from fully burning. Previous studies recommend an air-fuel ratio that is 1.6 to 2 times the stoichiometric ratio [32].

Airflow in cookstoves can be categorized as natural or forced draft. Natural draft stoves rely on the natural convection of hot gases rising to move air into the combustion zone. Forced draft stoves add an active airflow element, such as a fan, to more effectively pull oxygen into the combustion chamber. Compared to natural-draft stoves, forced-draft stoves can reduce fuel use by 40% and reduce emissions by 80 to 90% [26], [33]. However, forced draft stoves are more complex, as they need an external electricity source or thermoelectric power generation in order to power the fan [32]. With careful design, natural draft stoves can supply enough air for complete combustion [34]. Natural draft stoves are more sensitive to changes to stove geometry, which can affect airflow, and literature recommends that stove designs maintain a constant cross-section for the airflow pathway to prevent sudden changes in the flow [32], [34], [35].

A common method of increasing airflow to a stove's combustion zone without requiring forced draft elements is to place a grate with holes or perforations below the fuel. Grates allow air to more easily enter the combustion zone from beneath the fuel, and prevents accumulated char and ash from blocking airflow to the flame. Grates have been found to increase the thermal efficiency of cookstoves by 3 to 7% [32], [36]. Figure 2-2 shows the Mewar Angithi, a grate designed for three-stone fires, which has been shown to improve the fire's efficiency by 3%, decrease fuel use by 25%, and decrease emissions by 35% [37].

Figure 2-2: A grate insert known as the Mewar Angithi has been shown to improve the performance of three-stone fires [37].

Stove performance can also be improved by introducing secondary air to the combustion chamber. While primary air enters the stove where the fuel is located, secondary air enters the stove further downstream in order to solely react with the volatile gases released during the initial heating of the firewood. Secondary airflow ensures that more of the volatile gases are able to burn, reducing emissions. Secondary air can be introduced through additional air intake ports on the sides of the stove; a tall combustion chamber can also encourage oxygen to rise above the primary combustion zone. Both primary and secondary air can also be preheated before entering the stove, which reduces the amount of energy needed raise the air to combustible temperatures [34].

The combustion of volatile gases can also be encouraged by thoroughly mixing the gases with heated air. To promote mixing, there should be turbulent flow in the combustion chamber. Turbulent flow in cookstoves occurs at Reynolds numbers above 4000 [34]; the Reynolds number can be increased by increasing the airflow speed in the stove and by providing a larger cross-sectional area for mixing. Baffles and airflow choke rings along the airflow path, as shown in Figure 2-3, are also effective ways of promoting mixing and turbulent flow [25], [34].

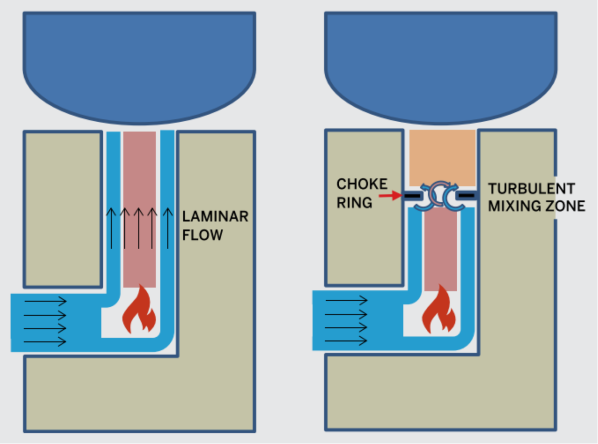


Figure 2-3: The addition of airflow choke rings can promote turbulent flow and mixing in a stove's combustion chamber [34].

The construction materials of a cookstove also impact the stove's performance. One material consideration is an object's thermal mass, or its ability to absorb and store heat, which is dependent on its density, volume, and specific heat capacity. Mud and clay, which are common traditional materials for homemade stoves, have high thermal mass; as a result, the body of the stove itself requires more energy to heat up when the fire is started. This can reduce the initial fire temperature and decrease heat transfer into the pot. Many improved cookstoves use metal as a construction material in order to reduce the thermal mass of the stove and improve durability; however, metallic stoves without sufficient insulation can have higher radiative heat transfer losses [32], [35].

Adding insulation to the combustion chamber also promotes the combustion of volatile gases by maintaining high temperatures in the stove. There are various ways to insulate the combustion chamber: foil can be added as a liner on the inside of the chamber to reflect heat, the combustion chamber can be sunken partially into the ground, or locally available materials such as hay, ceramics, or wood ash can be used as insulation [18], [34], [35]. Previous studies have found an 8% increase in efficiency and a 5% decrease in fuel consumption with improved insulation of the combustion chamber [36].

Beyond improving the stove's combustion dynamics, another important consideration in determining stove performance is the efficiency of the heat transfer from the hot gases to the cooking pot. Stove designs should maximize the surface area of the pot that contacts the combustion products, and the rising hot gases should be kept close to the cooking pot [35]. However, the flame itself should not contact the pot, which would rapidly cool the flame and decrease the combustion temperature [34]. Cooling the flame slows down or stops combustion reactions which reduce harmful pollutants.

The surface area of the pot in contact with hot gases can be increased by adding a small gap between the stove and the pot, which allows hot gases to rise out of the stove and pass over the sides of the pot. Another simple innovation that improves heat transfer is the pot skirt, shown in Figure 2-4, a thin strip of metal or other material that wraps around the pot in order to prevent rising hot gases from moving away from the sides of the pot. Pot skirts can reduce fuel use and emissions by 25 to 30% [33].

Figure 2-4: A pot skirt can keep rising hot gases close to the cooking vessel [35].

Two common styles of improved biomass cookstoves are rocket stoves and gasifier stoves. Rocket stoves have a tall, insulated chamber to promote cleaner-burning fires by providing more space for mixing and secondary combustion of volatile gases. The added height of rocket stoves can also help to induce natural convection and increase the speed of airflow into the stove. Rocket stoves are usually made with metal, and these manufactured rocket stoves are available internationally. Rocket stoves can also be locally made in rural areas with clay, stone, or bricks. Fuel is fed through an opening in the side of the rocket stove, and the stoves can be natural or forced draft [26]. Lab testing has shown that rocket stoves reduce fuel consumption by 33%, CO emissions by 75%, and PM emissions by 46% compared to a three-stone fire [33].

Gasifier stoves are designed with two combustion zones, one for pyrolysis where fuel is heated to produce combustible gases, and another for the combustion of the gases. This two-stage combustion makes gasifier stoves cleaner and more efficient; lab testing has found that gasifier stoves have efficiencies of 25 to 50% and reduce particulate matter levels by 90% compared to a three-stone fire [26], [32], [33]. However, one disadvantage of gasifier stoves is that they often require forced draft elements to provide enough oxygen to the flame [32]. Gasifier stoves also usually require a consistent, homogeneous fuel.

2.2.2 Stove Operation and Building Architecture

Beyond the design of the cookstove, improvements to a stove's operation can reduce stove emissions and fuel use. First, the size and moisture content of the firewood affects combustion dynamics. Smaller pieces of fuel have more surface area for heat transfer and burn more quickly [34]. Gathered firewood is often air-dried for only short amounts of time, leading to high moisture levels that slow combustion, lower fire temperatures, and increase pollutant levels [38]. Stoves operated with damp firewood with 25% moisture content have been found to be 20 to 25% less efficient compared to stoves operated with dry wood of 10% moisture; damp wood has also been found to increase carbon monoxide emissions [39].

Improving the speed and ease of stove ignition reduces household air pollution, as large amounts of smoke are released during the ignition phase where temperatures are too low for volatile gases to fully combust [34]. In firewood stoves, carbon monoxide emissions at ignition have been found to be two to three times greater than the emissions at steady-state combustion, and particulate matter can be as much as ten times higher [40]. Ignition emissions can be reduced by using more effective firelighters; top-down ignition methods have also been found to reduce carbon monoxide and nitrous oxide emissions compared to traditional ignition from the bottom of the fuel [39].

The method of fuel feeding can also impact stove performance. Continuous fuel feeding conserves fuel and maintains a stable flame height and location. However, in practice, stoves are frequently fed in batches since it is less time-consuming for the user, leading to inconsistent stove performance [34]. The cooking vessel can also be chosen to improve heat transfer from the hot gases to the pot. Metal pots will conduct heat more easily from the pot's surface to its contents, and stoves with larger surface areas in contact with the stove with receive more heat [35].

The use of alternative fuels for heating and cooking can also improve stove performance and reduce emissions. Many households in India own stoves that operate on liquified petroleum gas (LPG), although its cost and the difficulty of obtaining fuel refills discourage people from using LPG as their primary cooking fuel [16], [17]. Improved biomass fuels, such as charcoal briquettes made from agricultural waste and biomass pellets, have higher energy content and produce lower hazardous emissions levels compared to firewood [3], [25].

Outside of the cookstove itself, certain household architectural features can also improve cooking and heating outcomes. Many improved cookstoves incorporate chimneys into their design, which significantly reduces the amount of smoke entering the house [32]. The pressure differential created by chimneys also encourages natural convection and faster airflow into the stove, reducing fuel usage [41]. However, chimneys are not effective heat exchangers, and funneling hot gases to the outside can reduce the amount of heat transferred to the pot [33], [42]. Vertical chimneys without bends can also lead to household moisture issues during the rainy season, as water can enter the house through openings in the roof [41].

The need for space heating in the Himalayan region also contributes to household air pollution, and many improved space heating solutions for the region have been proposed. Traditional biomass-fueled heating stoves are improving in efficiency, and improved cookstove designs such as the rocket stove have also been proposed as potential heating solutions. More complex options for household heating are also being explored, including solar heating, heat pumps, and community-level heating networks. Improving home insulation or reducing the draftiness of households also reduce heat losses to the outside [3].

In the cold climates of the Himalayan region, many rural households use the same biomass stove for both heating and cooking [3], and it is important to note that certain common design changes for improved cookstoves impact household heating outcomes. For example, chimneys removing smoke from the house may also remove a portion of the heat generated by stoves, and radiative heat losses from sheet metal stoves reduce cooking efficiency but provide space heating. Stoves with a high thermal mass heat up slower upon ignition, but in drafty houses with high air exchange rates, heating a thermal mass can be more effective for space heating than directly heating the air [42]. Efforts to reduce household air pollution in the Himalaya face the unique challenge of the significance of both cooking and heating in the household energy system.

Chapter 3

Laboratory Testing of Stove Performance

Handmade traditional clay stoves, known as *chulha* in Hindi and *chulo* in Nepali, are common in rural communities throughout the Himalayan region. A model clay stove similar to those found in the Himalaya was constructed and tested in D-Lab. Water boiling tests were conducted with the stove under different conditions, including with kiln-dried and air-dried firewood and with prototypes of improvements made to the stove. The goal of these tests was to determine stove performance metrics, such as efficiency and pollutant emissions, for existing traditional stoves, as well as evaluate the effectiveness of the stove improvements.

3.1 Construction of the Model Stove

The model stove was based on traditional clay stoves found in the villages of the Chakrata district of Uttarakhand state, one of D-Lab's community partners in North India. Chakrata is discussed in more detail in Section 4.2.5, and a traditional stove in Chakrata is shown in Figure 3-1(b). The stove has a design common to South Asia and the Himalayan region. The stove's firebox is a horizontal central channel that opens towards the user; the firebox has multiple openings towards the top of the stove for cooking vessels. It was observed that stoves in Chakrata have either two or three openings for cooking pots on the top of the stove. For two-pot stoves, the second pot hole was located behind the first, in-line with the entrance to the firebox.

A review of the design catalogue for India's National Programme for Improved Chulhas revealed that many two-pot clay stove designs were 70 to 80 cm long, 30 to 40 cm wide, and 20 to 30 cm tall [13]. The catalogue also showed that side-by-side placement of the two cooking vessels was more common, but it was decided that the model stove should preserve the front-and-back pot placement seen in the stoves of our partner community.

The D-Lab model stove had two pot holes, and measures 62 cm long by 34 cm wide by 17 cm tall, which is slightly smaller than the typical two-pot stove. In most households, traditional clay stoves are built on a stationary platform on the floor of the house, but the D-Lab stove was designed to be smaller and lighter for ease of transport in and out of the fume hood testing setup. The stove was built on a steel baseplate, so that it could be easily moved. The model stove's pot holes measured 18 cm in diameter, and were chamfered inwards and sized to the pots used for the experiments. The firebox of the stove measured 15 cm wide by 10 cm tall, and extended to the back of the secondary pot hole. Figure 3-1(a) shows the model stove.

(a) (b)

Figure 3-1: The clay stove constructed in D-Lab (a), based on a traditional north Indian stove design in the Chakrata district of the Indian state of Uttarakhand (b).

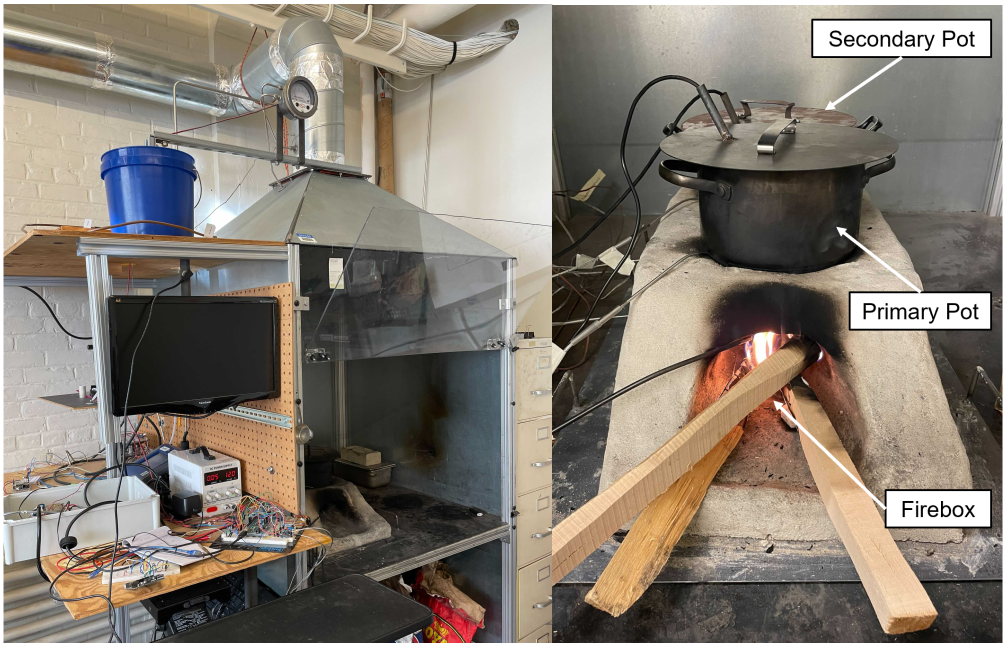
The model stove was constructed by hand from a mixture of sand and clay. The clay used was Hawthorn Bond Fireclay with a 40 mesh, or 0.42 mm, particle size [43]. The sand used was Pavestone Natural Play Sand [44]. The sand and clay were first thoroughly mixed together while dry, then water was added to the mixture until the material was malleable. Roughly 50 liters of the sand-clay mixture was used for the stove.

The ratio of sand to clay used for the stove was 3:2. This optimal ratio was experimentally determined by making bricks of different mixture ratios of sand and clay. The bricks were heated in an oven to 230°C in order to examine their consistency and structural performance at high temperatures. Bricks with too much sand had a tendency to crumble easily, while bricks with too much clay cracked under heat. Using the volume and weight of the bricks, the density of the 3:2 sand-clay mixture was found to be 885 kg/m^3. After the stove was constructed, it was air-dried for a week in a fume hood in D-Lab. Wooden molds were used to support the interior cavities of the stove as it dried.

3.2 Experimental Procedure for Laboratory Testing

The performance of the model stove was evaluated with the Water Boiling Test (WBT), a commonly used testing standard to determine cookstoves' efficiency and pollution levels through boiling pots of water. The WBT consists of three phases: cold start, where the water and the stove both begin at room temperature; hot start, where water is boiled on the already heated stove; and simmer, where the water is maintained at just below the boiling point for 45 minutes [45]. A shortened version of the WBT without the simmer phase was conducted in order to save time and fuel, as well as avoid the difficulty of maintaining the water at the a constant temperature on the firewood stove.

The model stove was tested in D-Lab's Burn Lab, an experimental setup for cookstove evaluation consisting of a fume hood equipped with temperature and pollution sensors. The sensors are connected to an Arduino Mega for datalogging. Figure 3-2 shows the Burn Lab's fume hood and the model stove undergoing a WBT in the fume hood, with the firebox and primary and secondary pots labeled.



(a) (b)

Figure 3-2: The Burn Lab fume hood (a), and the model stove being tested in the fume hood (b).

The Burn Lab data collection setup includes five thermocouples. One was placed in the fire, two were placed on the stove's inside surfaces beneath either pot, and two were placed in the gaps between the pots and the stove. In addition, the temperature of the water in each pot and the stove's surface temperature were measured with digital temperature sensors. Figure 3-3 shows the positioning of the thermocouples.

To determine the pollution levels within the wood smoke, a pump is attached to the Burn Lab's fume hood to continuously extract a sample of the fume hood exhaust. Part of this sample is routed into a particulate matter sensing system, and the rest is routed into a small container with sensors to measure the concentrations of oxygen, carbon monoxide, carbon dioxide, and nitrous and sulfur oxides. After these data are collected, the isolated exhaust rejoins the fume hood's main exit. Appendix A provides more details about the models and specifications of the sensors used in the Burn Lab.

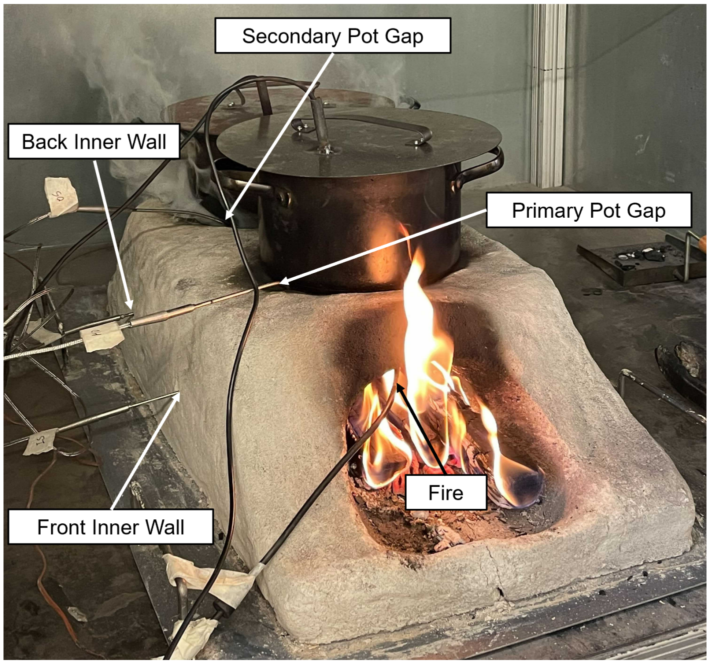


Figure 3-3: The locations of the fire, stove inner wall, and pot gap thermocouples for the Burn Lab model stove.

The D-Lab model stove was tested with two pots of water on the two pot holes of the stove. The primary pot, which was located in the front of the stove directly above the fire, was 19 cm in diameter and 11 cm in height, with a material width of 2.5 mm. The secondary pot was 21 cm in diameter and 10 cm in height, with a material thickness of 3 mm. Both pots were made of stainless steel. Two liters of water were placed in each pot, and lids were placed on the pots during the test. For both the cold start and hot start phases, the pots were heated until the water in the primary pot reached 90°C; the water was not allowed to reach its boiling point to avoid introducing uncertainties regarding the energy consumed by evaporation. At the transition between the cold start and hot start phases, both the water in the primary and secondary pots were replaced with room-temperature water.

Cooking fires in India are commonly started with dry grass, agricultural waste, paper, plastic, or kerosene [34]. For the WBTs in D-Lab, the fire was started using biomass firestarter cubes [46] in order to achieve a consistent ignition procedure. During stove operation, it was observed that the flames were pulled towards the back of the stove, and it was sometimes difficult for the flames to propagate onto the unburned sections of firewood at the mouth of the stove. If the fire went out during a test due to this phenomenon, another biomass firestarter was used to relight it.

In accordance with local cooking practices in India and Nepal, the fire was tended throughout the cooking process with the goals of containing the fire within the stove and maintaining a consistent flame beneath the primary pot. Pieces of firewood were rested on the raised lip of the stove's firebox, which allowed airflow to flow beneath the wood and into the flame. Throughout the test, a container of firewood was placed on a load cell connected to the Burn Lab's data acquisition system, allowing the rate of wood consumption to be measured as wood was moved from container to stove. The remaining char and ash were also weighed at the end of each test. At the end of each test, the pots of water were removed from the stove and the fire was allowed to burn out naturally.

The char and ash that accumulated in the firebox were cleaned out after each test. During most tests, cracks appeared around the stove's firebox due to the high temperatures. After every test, these cracks were repaired with the same mixture of sand and clay that the stove was made from. The cracks were more prominent in the initial few tests, but continued to be present throughout all the tests. The stove may be more susceptible to cracking due to an imperfect ratio of sand and clay in the construction material; more effort should be made to refine the mixture if more clay stoves are to be made in the future. The stove stayed warm for a considerable time after each test, and the tests were spaced at least one day apart to allow the stove to fully cool down.

A few parameters of the cookstove's operation were varied throughout the tests, including the species of the firewood, the drying method of the firewood, and the addition of minor improvements to the stove. Kiln-dried, store-bought mixed hardwood [47] was used for most of the tests. The firewood was cut to pieces of between 2 cm and 4 cm in width in order to fit in the stove. The firewood pieces were roughly 40 cm in length. The moisture content of the kiln-dried wood was measured to be between 5% and 11%. Six tests were performed under the base condition, with kiln-dried firewood and no modifications to the stove. The results of the first two tests are not included in the averages presented in Section 3.3, since there were issues with some of the temperature and pollution sensors, and the team was less well-practiced at tending the fire, which may have impacted the stove's performance.

Four tests were also performed with air-dried firewood available in D-Lab and no modifications to the stove. Two of these tests were performed with air-dried birch wood, with a moisture content of between 7 and 14%. Due to a lack of sufficient birch wood, the other two tests were performed with cedar wood, with a moisture content of between 4 and 7%.

Two clean cooking solutions were tested on the D-Lab stove: a grate, to improve airflow to the fire, and pot stands, to create a gap between the stove and pot out of which hot gases could rise. The tested solutions can be seen in Figure 3-4, with the prototypes of the grate and pot stands on the left of the photograph, and the final versions on the right. Figure 3-5 shows the grate and pot stands being tested on the model stove. The grate and the pot stands were both tested using kiln-dried mixed hardwood.

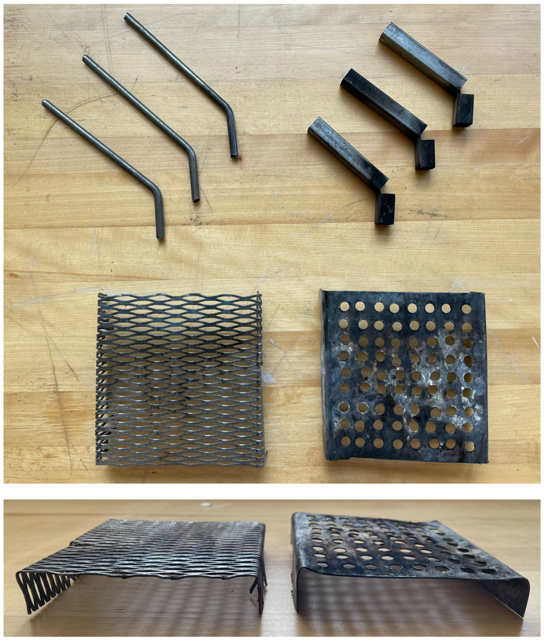


Figure 3-4: The prototype (left) and final (right) versions of the grate and pot stands tested on the D-Lab model stove.

The grate was based on the Mewar Angithi grate for open fires and three-stone fires discussed in Section 2.2; the Mewar Angithi is shown in Figure 2-2 [37]. The grate is intended to create a path for airflow into the flame from beneath the firewood, as well as provide a space for ash to settle away from the burning fuel. The first grate prototype was made with a perforated steel sheet. Due to supply chain considerations, the final prototype was made of sheet metal punched with an array of holes, which would be easier to source and manufacture in remote areas. Both grates were square and measured 12 cm by 12 cm, and were 2.5 cm tall and with 1 mm thick material. During operation, the grate was placed at the mouth of the stove, and firewood was placed on the grate; this can be seen in Figure 3-4(a).

(a) (b)

Figure 3-5: The grate (a) and pot stands (b) being tested in the Burn Lab on the model stove.

Appropriately sized pot stands are a common improvement for firewood stoves. Pot stands slightly elevate the pot above the stove in order to allow hot gases from the fire to flow up and around the pot. In Figure 3-4(b), it can be seen that when the pot stands are in place, flames are rising along the side of the pot. The prototype pot stands were made of mild steel rod 0.5 cm in diameter, bent to match the chamfer angle of the pot holes. However, it was difficult to keep the pots in place on the round rods. The final version of the pot stands were therefore made with mild steel square tubing 1 cm in side length, also bent to match the chamfer of the pot holes. A groove was cut where the pot stand bent to provide a notch for the pots to rest upon, as seen in Figure 3-6. When operating the stove, three pot stands were spaced evenly around the perimeter of each pot hole for the pot to rest on.

Six tests were conducted with the grate and five tests were conducted with the pot stands, but two tests per solution were not included in the final averages presented in Section 3.3. The first test with each solution was performed with the initial prototypes, and those tests were not included in the data averages. One test for each solution was also conducted with the fume hood face barrier lowered in the Burn Lab, which influenced the performance of the solutions. The Burn Lab can be seen in Figure 3-2(a), with a piece of clear plastic across the face of the hood in a raised position. When this door is lowered, it prevents stove emissions from entering the room, but also blocks most of the entrance to the fume hood, leaving a 20 cm tall space to allow air to enter the mouth of the stove. Lowering the fume hood face barrier was found to negatively impact the performance of the pot stands; as a result, the tests with the barrier lowered were not included in the data averages for the grate and pot stands reported in Section 3.3. Two tests with air-dried wood were also performed with the fume hood face barrier lowered, but as it did not seem to impact the stove's performance, those tests were included in the averages presented.

Figure 3-6: A cooking pot resting on the notch cut into the final design of the pot stands.

3.3 Model Stove Test Results

Figures 3-7 and 3-8 show the temperatures and pollution levels during one of the tests with kiln-dried firewood and no modifications of the stove. Figure 3-7 shows the temperatures of the the two pots of water, the fire, the inner wall temperatures of the front and back of the stove, and the temperatures of the small gaps between the pot and the stove for both the primary and secondary pots. The locations of the thermocouples within the model stove are shown in Figure 3-3.

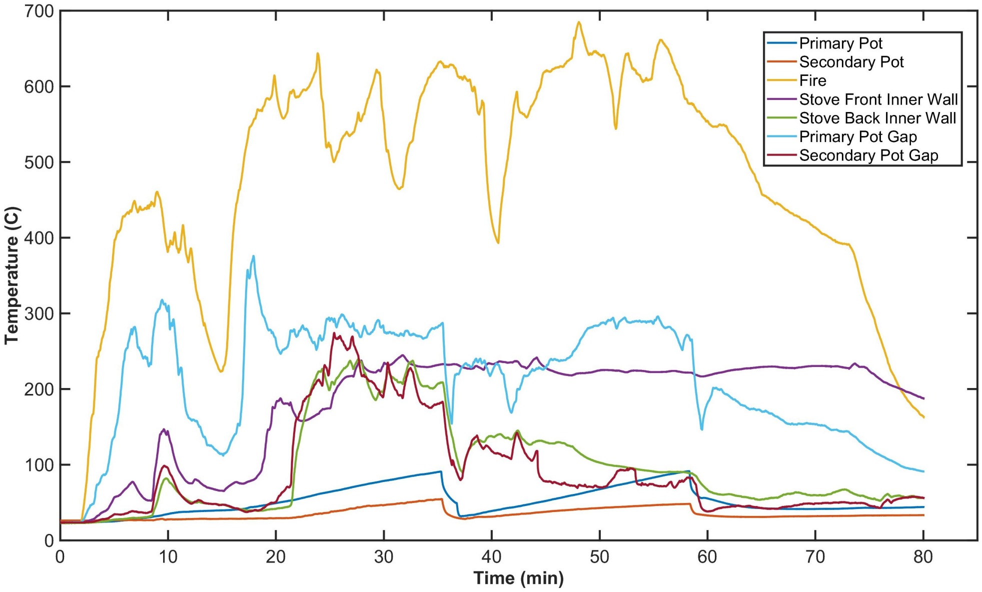


Figure 3-7: The temperatures of the pots of water, the fire, and various points on the D-Lab model stove throughout a water boiling test.

The water temperature in the primary and secondary pots increase through the cold start phase, drop when the water is replaced, and then increase again through the hot start phase. The temperature of the secondary pot increases slower than the temperature of the primary pot. Roughly 15 minutes into the test shown in Figure 3-7, there is a drop in the temperatures of the fire, pot gaps, and stove surfaces. This is due to the fire burning low; another firestarter was added during this test to sustain the flame. After that, the fire temperature remains largely constant throughout the test. The occasional dips in fire temperature can be attributed to the fire shifting in location throughout the test; as a result, the thermocouple measuring fire temperature was not always directly within the flame, and the actual flame temperature is likely much higher than the measured temperature.

The primary pot gap temperature was generally higher than the secondary pot gap temperature, and the front inner wall of the stove was at a higher temperature compared to the back inner wall. At the beginning of the test, the fire may have extended further back into the stove, causing the higher temperatures of the back inner wall and the secondary pot gap. It can be seen that the operation and environment within the stove varies even within the same test.

Figure 3-8 shows the levels of CO, CO_2, NO, NO_2, SO_2, and PM 2.5 for the same test as Figure 3-7. The operation of the stove leads to slight increases in NO, NO_2, and SO_2, but there are only trace concentrations below 10 ppm, as fire temperatures were not high enough to form more significant levels of those pollutants. As a result, NO, NO_2, and SO_2 were not considered in comparing the stove's performance under different conditions. There were more significant levels of carbon monoxide, which reached maximums of near 60 ppm. Ambient carbon dioxide levels in the room where the Burn Lab is located are slightly above 500 ppm, and CO_2 levels rise in the stove exhaust to above 2000 ppm during the test. There were also significant levels of PM 2.5, which measured near 300 mg/m^3 in this test. The pollutant concentrations were highest in the middle of the test, but smaller spikes of CO and PM 2.5 can be seen near the 80-minute mark when the fire went out.

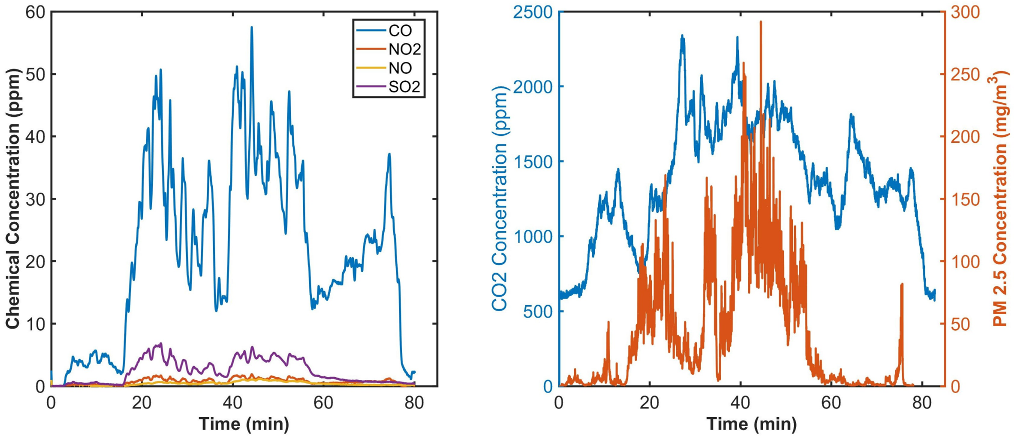


Figure 3-8: Levels of pollutants throughout a water boiling test on the D-Lab model stove, including the fire's ignition and burnout.

Equations 3.1 through 3.6 were used to calculate indicators of stove performance, including the average power into the cooking pots, pot power ratio, average firepower, thermal efficiency, and emissions rates and emissions factors.

The average power into the cooking pots ($\dot{Q_{pot}}$) was calculated by dividing the total energy used to heat the water in both pots by the length of the test.

$$\dot{Q_{pot}} = \frac{\dot{m_{water}} c_{p,water} (\Delta T_{pot1} + \Delta T_{pot2})}{\Delta t} \tag{3.1}$$

The pot power ratio ($r_{potpower}$) was defined as the ratio of the power entering the primary pot to the power entering the secondary pot. This stove performance indicator was developed for this study in order to assess the power distribution between the stove's two cooking vessels.

$$r_{potpower} = \frac{\Delta T_{pot1}}{\Delta T_{pot2}} \tag{3.2}$$

The firepower ($\dot{Q_{fire}}$) was calculated from the heating value of the firewood used, the mass of firewood burned, and the length of the test. The heating value varied depending on the specific species of firewood that was burned; these heating values can be found in Appendix B. The fire sometimes burned beyond the duration of the test, and was allowed to burn out naturally. In those cases, the total burning time of the fire is used to calculate the firepower instead of the length of the test.

$$\dot{Q_{fire}} = \frac{\Delta m_{wood} HV_{wood}}{\Delta t} \tag{3.3}$$

The thermal efficiency of a stove ($\eta_{thermal}$) is defined as the percentage of energy contained within the burned fuel that is useful for the cooking task. The efficiency was therefore calculated as the ratio of the average power into the pots to the average firepower.

$$\eta_{thermal} = \frac{\dot{Q_{pot}}}{\dot{Q_{fire}}} \tag{3.4}$$

The emissions factor (EF) is defined as the mass of a pollutant released per energy that enters the cooking vessels. The emissions (ER) rate is the mass of a pollutant released per time during the test.

$$EF = \frac{m_{pollutant}}{Q_{cooking}} \tag{3.5}$$

$$ER = \frac{m_{pollutant}}{t_{test}} \tag{3.6}$$

A mass balance of the carbon released in biomass fuels was used to calculate the mass of different pollutants emitted. For the purposes of analyzing the combustion process, firewood was modeled as cellulose, or $C_6H_{10}O_5$. A similar analysis can be performed for other biomass fuels using different chemical formulae. The total mass of carbon generated by the combustion of firewood ($m_{carbon,total}$) was found using the mass of wood burned and the molecular weight of the carbon within the wood. In the firewood combustion process, carbon emissions form either CO_2, CO, or PM 2.5, which can be assumed to be 80% carbon by mass [45]. The chemical concentration (C_i) of each pollutant was used to find the mass allocations of carbon between the different pollutants ($m_{carbon,i}$). From the carbon masses, the molecular weights of each pollutant (M_i) were used to find each individual pollutant mass (m_i). Molar concentrations were first converted to mass concentrations before the summation of the chemical concentrations. Equations 3.7 through 3.13 show the calculation process used for finding the mass of emitted pollutants from the measured pollutant concentrations and the mass of fuel burned. In cases where the fire burned beyond the end of the test, only the portion of fuel estimated to have burned during the test was taken into account.

$$C_{carbon,PM2.5}[g/m^3] = 0.8(C_{PM} - C_{PM,ambient}) \tag{3.7}$$

$$C_{carbon,CO_2}[ppm] = C_{CO_2} - C_{CO_2,ambient} \tag{3.8}$$

$$C_{carbon,CO}[ppm] = C_{CO} - C_{CO,ambient} \tag{3.9}$$

$$C_i[g/m^3] = C_i[ppm]M_i\frac{P}{RT} \tag{3.10}$$

$$m_{carbon,total} = m_{wood}\frac{M_{C6}}{M_{C6H10O5}} = m_{carbon,CO} + m_{carbon,CO_2} + m_{carbon,PM} \tag{3.11}$$

$$m_{carbon,i} = m_{carbon,total}\frac{C_{carbon,i}}{C_{carbon,CO_2} + C_{carbon,CO} + C_{carbon,PM}} \tag{3.12}$$

$$m_i = m_{carbon,i}\frac{M_i}{M_{carbon,i}} \tag{3.13}$$

Tables 3.1 through 3.4 list the average stove performance parameters, pollution levels, emissions factors and emissions rates, and various temperatures for the tests performed on the model stove. Four tests were included in the average for the standard, air-dried wood, and grate conditions, and three tests were included in the average for the pot stands. The full results for all of the tests conducted can be found in Appendix C.

The sets of results for each condition were compared using two-sample t-tests to determine whether or not there were statistically significant differences between the test conditions. The test used was a two-tailed Welch's t-test, with variances assumed unequal and a significance level α of 0.05. For parameters that had statistically significant differences, the hypothesized mean difference between the two conditions was calculated.

In addition to the stove performance parameters described above in Equations 3.1 through 3.4, Table 3.1 also displays the average test duration and mass of fuel used for each test condition. The test duration, firepower, power into the pots, and the stove's thermal efficiency were similar for all conditions, and there were significant changes in fuel use and pot power ratio for the tests performed with pot stands.

The thermal efficiencies of the D-Lab model stove measured between 13 and 16% for all conditions. Previous studies have found traditional clay stoves' thermal efficiencies to be between 5 and 15% [13], [29]–[31]. The D-Lab model stove performed towards the upper end of this commonly accepted range of efficiencies. The stove likely performed better in the lab than it would have in the field, due to the controlled conditions, the effective firestarters, and the low moisture content of the firewood.

Condition	**Fuel Use (kg)**	**Test Duration (min)**	**Firepower (W)**	**Pot Power (W)**	**Pot Power Ratio (-)**	**Efficiency (%)**
Base Condition	0.822	48.0	3666	479	4.07	13.18
Air-Dried Wood	0.802	59.8	3098	469	3.04	14.42
Grate	0.699	59.5	2948	446	2.43	16.28
Pot Stands	0.487	47.2	2689	436	20.12	15.83

Table 3.1: Key parameters of stove performance at different test conditions for the D-Lab model stove.

There were no significant differences between the stove's performance with kiln-dried firewood and air-dried firewood. This may have been due to the moisture content of the two categories of wood being roughly the same. The air-dried wood had been drying indoors in D-Lab for an extended period of time, and it had moisture levels of only 4 to 14%. However, it was observed that the air-dried wood was more difficult to light during the tests, and in the future, tests could be conducted with wood of higher moisture content.

The grate did not significantly improve the stove's performance for any of the key metrics listed in Table 3.1. Similar grates have been shown to improve the performance of open fires and three-leg pot stands [32], [36], [37]. However, the design of the model stove was less suitable to the addition of a grate. The raised lip of the firebox already elevates the pieces of wood above the bottom of the stove, which allows airflow into the base of the flame. The grate is therefore somewhat redundant with the firebox lip, and when the grate was positioned at the front of the firebox, the raised lip impeded airflow into the area beneath the grate. The grate also reduced the available firebox volume, which decreased the amount of wood that could be placed in the fire and limited the space for volatile gases released from the fire to rise and mix. The grate did not reduce ash buildup in the fire, as most of the ash and char are pushed towards the back of the stove. The grate did make the fire easier to maintain; without the grate, firewood pieces had to be carefully placed to allow a path for airflow into the flame. However, the grate also made it more difficult to see the status of the fire further back in the stove.

Unlike the grate, the addition of pot stands had an effect on the stove's performance. With pot stands, there was a statistically significant decrease to the mass of fuel used and a statistically significant increase to the pot power ratio. The hypothesized mean difference was 0.17 kg for fuel use and 3.80 for the pot power ratio. However, adding pot stands did not significantly change the total power into the pots or the stove's thermal efficiency. There was a similar amount of energy from the fire entering the pots, but the energy was more unevenly distributed between the primary and secondary pots. This resulted in the primary pot heating up much faster, decreasing the test duration. This aligns with the observation that the pot stands made the flame more stationary below the primary pot, instead of being pulled towards the back of the stove.

Table 3.2 shows the average and maximum levels of CO, CO_2, and PM 2.5 for each of the test conditions. The carbon monoxide sensor stopped providing reliable data in the latter half of the tests, so no CO levels are reported for the tests with grates and pot stands. There were high levels of particulate matter for all conditions, although adding pot stands seemed to lower particulate matter levels. The grate displayed a statistically significant drop in CO_2 compared to the standard condition, with a hypothesized mean difference of 59 ppm, which could be due to the grate allowing more oxygen to enter the fire from below. The pot stands also showed a statistically significant drop in CO_2, with a hypothesized mean difference of 47 ppm. This may be due to the gap that the pot stands create, which provides more space for the flame to burn completely.

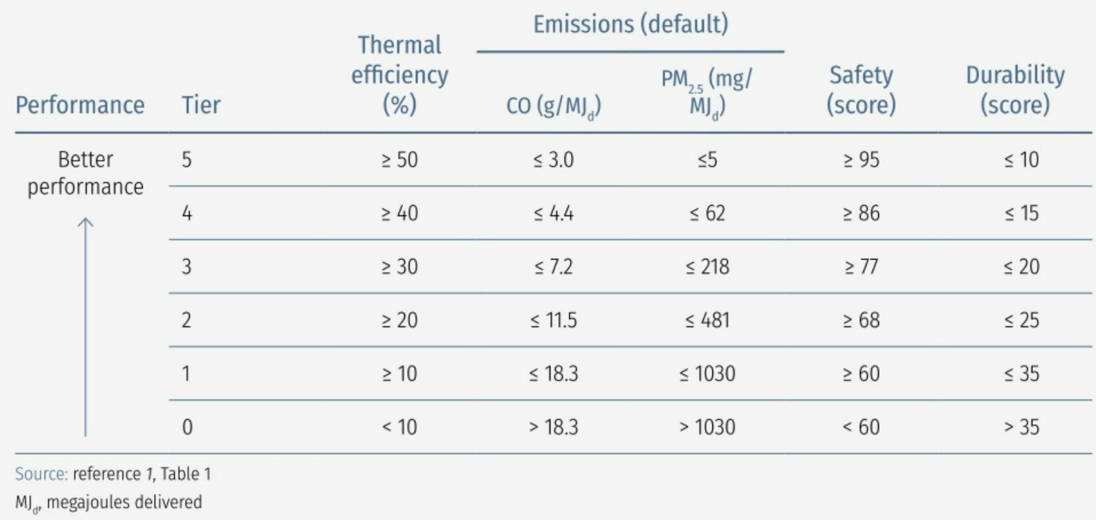
Condition	**Avg CO_2 (ppm)**	**Max CO_2 (ppm)**	**Avg CO (ppm)**	**Max CO (ppm)**	**Avg PM2.5** (mg/m^3)	**Max PM2.5** (mg/m^3)
Base Condition	1475	2207	24	60	53	257
Air-Dried Wood	1106	1539	14	34	21	153
Grate	1168	1821	-	-	38	241
Pot Stands	1286	2006	-	-	8	73

Table 3.2: Average and maximum levels of pollutants for different test conditions for the D-Lab model stove.

Average emissions rates and emissions factors were also calculated for the standard condition using the carbon balance method, but there were insufficient pollution data to perform the same analysis for the other three conditions. CO_2 made up most of the carbon emissions from the stove. Emissions factors for CO and PM 2.5 both measured an order of magnitude below that of CO_2, and emissions of PM 2.5 were roughly double that of CO. These emissions statistics can be compared to the voluntary performance targets for biomass cookstoves developed by the International Organization for Standardization (ISO) in 2018, which are shown in Figure 3-9 [48]. The model stove's CO emissions factor meets the standard for performance Tier 1. However, the PM 2.5 emissions factor ranks at the lowest Tier 0, being more than an order of magnitude above the standard to reach Tier 1. The thermal efficiency of the stove ranks at Tier 1, as it is above 10%.

	Emissions Factor (g/MJ)	**Emissions Rate (g/min)**
CO	13.9	0.387
CO_2	717	20.0
PM 2.5	28.4	0.801

Table 3.3: Emissions factors and emissions rates for the model clay stove, under the standard testing condition.



Performance	Tier	Thermal efficiency (%)	Emissions (default) CO (g/MJ$_d$)	Emissions (default) PM$_{2.5}$ (mg/MJ$_d$)	Safety (score)	Durability (score)
Better performance	5	≥ 50	≤ 3.0	≤5	≥ 95	≤ 10
	4	≥ 40	≤ 4.4	≤ 62	≥ 86	≤ 15
	3	≥ 30	≤ 7.2	≤ 218	≥ 77	≤ 20
	2	≥ 20	≤ 11.5	≤ 481	≥ 68	≤ 25
	1	≥ 10	≤ 18.3	≤ 1030	≥ 60	≤ 35
	0	< 10	> 18.3	> 1030	< 60	> 35

Source: reference 1, Table 1

MJ$_d$, megajoules delivered

Figure 3-9: Voluntary performance targets for biomass cookstoves, developed by the ISO in 2018 [48].

Table 3.4 shows the average temperatures at various points in the stove environment for the different test conditions. Fire temperatures remained largely constant throughout the different conditions; the drop in fire temperatures for the pot stands was not statistically significant. It can be seen that primary pot gap temperatures are generally higher than secondary pot gap temperatures, and that front inner wall temperatures are higher than back inner wall temperatures. Stove surface temperatures were not measured for the initial tests. In the later tests, it can be seen that the surface temperatures are much lower than the stove interior temperatures, due to clay's high thermal mass.

Condition	**Fire (°C)**	**Gap 1 (°C)**	**Gap 2 (°C)**	**Inner Wall 1 (°C)**	**Inner Wall 2 (°C)**	**Surface (°C)**
Base Condition	540	280	106	168	65	-
Air-Dried Wood	528	345	144	201	96	47
Grate	529	412	162	266	83	39
Pot Stands	367	410	25	188	-	44

Table 3.4: Average temperatures of various locations within the D-Lab model stove for different test conditions.

The addition of the grate led to statistically significant increases in the primary gap temperature, secondary gap temperature, and the front inner wall temperature. This was most likely due to the firewood being raised up on the grate, positioning the fire higher in the firebox and closer to the pot gap and inner wall thermocouples. Char and half-burnt pieces of wood tended to fall behind the grate and pile up in the back of stove due to the reduced firebox volume, which could have also contributed to the increase in secondary gap temperature.

The pot stands showed a statistically significant increase in primary gap temperature and a statistically significant decrease in secondary gap temperature. This corresponds with the sharp decrease in the pot power ratio; the primary pot gap has higher temperatures due to the flames coming through the gap, and the energy going to the secondary pot is reduced. The back inner wall temperature for the pot stand tests is likely to also have significantly decreased, but that particular thermocouple had unreliable readings for the last few tests.

Though the tests with the initial solution prototypes and the solution tests with the fume hood face barrier lowered were not included in the results presented in the tables above, they also provide important insights into stove performance. The prototype pot stands seemed to perform better than the final versions; the stove's efficiency in that test was 21.14%, more than 5% higher than the average efficiency of the final version of the pot stands. This may be due to the smaller diameter of the prototype pot stands, which channeled hot gases through a smaller gap so that more heat was forced to contact the pot. An experimentally validated computational heat transfer model for biomass cookstoves from existing literature also found that decreasing this gap size increased thermal efficiency [49].

Lowering the fume hood face barrier significantly decreased the performance of the pot stands. The efficiency of that test was only 10.93%, and the pot power ratio was 2.46, a similar ratio as measured for the other conditions. Since the airflow rate through the fume hood face is constant, lowering the barrier increased the air velocity. It was observed that this stronger draft from the lowered barrier prevented the flame from stabilizing beneath the primary pot and discouraged flames from rising out of the pot gap.

Parameter	**Cold Start Average**	**Hot Start Average**	**Hypothesized Mean Difference**
Phase Duration (min)	32.4	21.7	6.6
Power Into Pots (W)	393	505	41
Pot Power Ratio (-)	6.54	6.82	-
Efficiency (%)	12.76	17.44	2.22

Table 3.5: Average stove performance metrics for the cold start and hot start phases of the water boiling tests performed in the Burn Lab.

Table 3.5 shows the averages of key parameters for the cold start and hot start phases for all tests analyzed in the previous tables, as well as the hypothesized mean difference for statistically significant differences. Overall, the stove performs better during the hot start phase: the phase duration is decreased, more power enters the pots, and the thermal efficiency increases. The large thermal mass of the clay stove leads more heat to enter the body of the stove and less heat to enter the pots at first.

In addition, the fire burns with less power upon ignition. There were no significant changes to the pot power ratio between the cold start and hot start phases.

3.4 Conclusions from Laboratory Tests

A model clay stove was built in D-Lab with a similar design to the traditional clay stoves of Chakrata district, Uttarakhand, one of D-Lab's community partners in north India. The stove was made by hand out of a mixture of sand and clay, and it measured 62 cm long, 34 cm wide, and 17 cm tall. A hollow firebox extended for most of the stove's length, and the stove accommodated two cooking pots.

The clay stove's performance was evaluated with a shortened version of the water boiling test, with only the cold start and hot start phases included. The stove was tested under the standard condition of using kiln-dried wood with no modifications to the stove, and tests were also performed under three additional conditions: air-dried wood with no modifications to the stove, kiln-dried wood with a grate added, and kiln-dried wood with pot stands added. Three to four tests were performed for each condition. Welch's t-tests were used to evaluate the differences between the base condition and the other conditions.

For all conditions, the stove displayed average efficiencies of between 13 and 16%. These efficiencies lie within the upper range of reported traditional clay stove thermal efficiencies from previous studies [13], [29]–[31]. With the exception of the pot stand condition, the ratio of energy entering the primary pot to energy entering the secondary pot was found to be between 2 and 4. The average power entering the pots measured between 400 and 500 W for all conditions, and the firepower varied between 2600 and 3700 W. The stove performs better during the hot start phase of the water boiling test, with decreased test duration, increased power into the pots, and increased thermal efficiency.

The stove's operation caused significant increases in CO, CO_2, and PM 2.5, and the stove also emitted trace concentrations of NO_2, NO, and SO_2. Both the pot stands and grate decreased the measured CO_2 levels, though they did not lead to any statistically significant changes in PM 2.5. Fire temperatures averaged between 500 and 600°C. However, it should be noted that fire temperature is difficult to measure accurately, and the thermocouple was not always within the flame, so the actual flame temperature is likely much higher. The temperatures of the pot gap and inner wall at the front of the stove were generally higher than the temperatures in the back. Stove surface temperatures were considerably lower than stove interior temperatures.

There were no significant differences in stove performance, pollution levels, or stove temperatures with the air-dried wood. This is likely due to the air-dried wood having similar moisture content as the kiln-dried wood. Air-dried wood with higher moisture content, similar to what is found in the field, should be tested in the future.

The grate was not effective at improving the stove's performance. The raised lip of the firebox in the stove's design already provided airflow to the fire, the addition of the grate reduced available space in the firebox, and the airflow provided by the grate did not extend beyond the opening of the firebox. The grate led to statistically significant increases to the primary pot gap and the front inner wall temperatures, due to the grate elevating the location of the fire within the stove. The addition of grates to stoves of this design may need to be coupled with changes in stove dimensions to maintain firebox size. A long thin grate insert that extends far back into the stove may also be a better form factor for this stove.

The pot stands significantly changed the stove performance; there was a statistically significant decrease in fuel use and a statistically significant increase in the pot power ratio. The pot stands distribute the energy entering the pots more unevenly, but does not increase the total power into both pots or the stove's thermal efficiency. More data needs to be gathered on communities' opinions of such changes to the stove's performance. Pot stands also decreased some emissions levels, increased the primary pot gap temperature, and decreased the secondary pot gap temperature.

The test of the pot stand prototypes showed that a smaller pot stand and therefore a smaller gap between the stove and pot may increase the solution's performance. An additional test performed with the fume hood's face barrier lowered shows that pot stands may be less effective with faster airflow speeds into the stove, which may make that particular solution non-compatible with the draft introduced by the addition of a chimney. Pot stands also lead to more smoke coming out of the pot gap and into the kitchen, rendering chimneys less effective.

Going forward, some improvements should be made to the Burn Lab setup, and there are many new avenues of experimentation to be explored. The load cell that measures firewood weight throughout the test does not have the capability to accommodate the weight of the model stove. Ideally, a new load cell with a higher capacity could be implemented, which would allow the exact amount of wood in the cookstove to be measured throughout the test, offering higher-fidelity data on the rate of fuel use. In addition, the pollution sensors should be made more reliable, as pollution data collection was hampered by intermittent or inaccurate readings on both the carbon monoxide and particulate matter sensors. Data analysis methods could also be further refined, as the efficiency calculation did not take into account the energy contained within the firestarters and the amount of char remaining at the end of the test, and the energy required to vaporize the water contained within the firewood was not considered.

An important step in the future is to evaluate the effects of adding a chimney to the model stove; this chimney can be either fully made out of clay or take the form of a metal tube molded into the clay. Chimneys are a common and effective solution to remove pollutants emitted from firewood stoves from the interior of a home. However, installing a chimney increases the draft through the stove, which could change the stove's performance and reduce the effectiveness of certain stove modifications, such as pot grates. A chimney also increases heat losses to the outside through chimney exhaust, reducing the space heating that the stove can provide. In order to assess the magnitude of these changes, an anemometer should be incorporated into the Burn Lab for measuring the chimney airflow speed, and a thermocouple should be installed to measure the chimney exhaust temperature. Ideally, the chimney should be removable, so that the chimneyless model stove could still be tested.

More tests should be performed to further improve the grate and pot stands. Subsequent prototypes of the grate could explore thinner, longer form factors, allowing the grate to extend further back into the firebox. Future prototypes of the pot stands could be made with a smaller size of metal stock, as a smaller pot gap may improve the pot stands' performance. The effect of other modifications on the model stove's performance should also be explored. Future solutions that could be considered include adding a pot skirt in conjunction with the pot gap to channel hot air along the sides of the pot, or adding internal baffles to induce turbulent flow. The effects of changes to the stove's operation should also be investigated. These changes could include the size and form factor of the cooking pots, the amount of fuel placed in the fire, the moisture content of the firewood, and the method of ignition.

There is also the possibility of constructing and testing other Himalayan stove designs in the Burn Lab. The current stove is slightly smaller than the typical household cookstove in South Asia, and a full-scale stove could be built in the future. The team is collaborating with stove manufacturers in India and Nepal, and the capabilities of the Burn Lab could be used to test the performance of these manufacturers' stoves and improve their designs.

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Chapter 4

Field Experiments in Himalayan Communities

D-Lab is collaborating with universities in India and Nepal and rural communities in the Himalayan region in order to better understand biomass cookstove performance and develop household energy solutions. Data regarding cooking and space heating practices, ambient household and outdoor conditions, and stove performance have been collected from surveys and sensors.

Most of the data presented in this thesis was collected by a D-Lab team, including me, who visited India and Nepal in January 2022. The team was joined by researchers and students from our university partners, the University of Petroleum and Energy Studies (UPES) in Dehradun, India, and Kathmandu University (KU) in Dhulikhel, Nepal. On the trip, data were collected in various towns and villages located near Dehradun and Kathmandu, which are shown on the map in Figure 4-1.

The exception to this is the survey data and ambient household condition data from Chakrata, which were collected by UPES researchers over a longer period of time. The initial surveys about household cooking practices were conducted in the winter of 2020, and long-term data collection on ambient household conditions in Chakrata was performed in the fall and winter of 2021.

This section provides an overview of the qualitative and quantitative methods of data collection used during the January 2022 trip. Then, the research findings from each village and town are presented and compared to draw overall conclusions about household energy in the Himalayan region.

Figure 4-1: The locations in India and Nepal where data were collected in the field.

4.1 Methods of Data Collection

Both qualitative survey data and quantitative data regarding household conditions and stove performance were collected at each of the locations indicated in Figure 4-1. The surveys included questions about demographic information about the household, cooking and heating fuels, firewood collection and cooking practices, stove design and construction, and house construction and layout. Consent was obtained from all interviewees before the surveys, and the study was approved by MIT's Institutional Review Board. Photographs of stoves were also taken with consent of the interviewees. The surveys were conducted by researchers and students from UPES and KU who spoke the local languages. The full text of the survey can be found in Appendix D.

Two different types of dataloggers were used for data collection on ambient household conditions. The first of these was the Sensen datalogger, a commercial sensor platform first developed by D-Lab researchers [50]. These sensors take the form of a compact box, and record data from a single location where the box is placed. The Sensen dataloggers record temperature, humidity, and the levels of pollutants, including PM 2.5, PM 10, carbon dioxide, and carbon monoxide. These dataloggers were also were used for the collection of ambient household data by the UPES team in Chakrata.

Another sensor datalogging system was developed before the trip to compare indoor and outdoor temperatures and to assess stove use patterns. These wired sensors were intended to supplement the data from the Sensen dataloggers, since the Sensen boxes could only measure the ambient conditions at one location. This supplemental datalogger consisted of two digital temperature and humidity sensors for indoor and outdoor ambient conditions and one digital temperature sensor to measure stove surface temperatures. The Arduino Pro Mini was used as a microcontroller for this sensor setup. Figure 4-2 shows both the Sensen and supplementary dataloggers. The manufacturers and models of the sensors can be found in Appendix A.

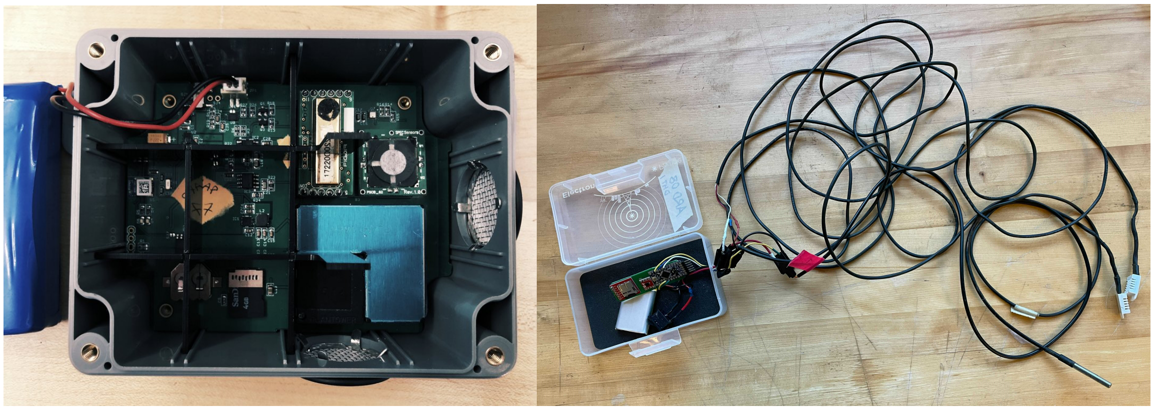

(a) (b)

Figure 4-2: A Sensen datalogger with the lid removed (a), and the supplemental multi-location temperature datalogger (b).

In addition to collecting data on ambient household conditions, water boiling tests (WBTs) were also conducted on stoves in actual kitchens to assess their performance. The WBT procedure was similar to the one followed during lab testing, as described in Section 3.2 [45]. A known quantity of water was brought close to its boiling point, and the temperatures of the fire and stove environment were recorded throughout. Each test consisted of a cold start phase, where the stove and pot were initially at ambient temperatures, and a subsequent hot start phase, where the fire was already lit and the stove was warm from the previous phase. The firewood to be used was weighed before each test, and its moisture content recorded. The firewood was weighed again after each of the cold start and hot start phases. Weighing the fuel between phases required the fire to be briefly put out, but was deemed necessary due to many stoves having burn rates that varied significantly over time.

Each phase of the WBT was stopped when the water was near boiling; the water was not allowed to reach its boiling point to prevent measurement uncertainties in the energy transferred to the pot that would result from water evaporating. The boiling point of water changes with elevation, so the stopping temperature of the tests changed between different villages. To conserve water, the water in the primary pot was switched out between the cold start and hot start phases, but unlike in the tests performed in the Burn Lab, the water in the secondary pot was not changed.

Data from the water boiling tests were recorded using a scaled-down version of the Burn Lab setup in D-Lab. Two thermocouples recorded the temperatures of the fire, pot gap, and other high-temperature areas. Five digital temperature sensors were use to collect data from other relevant locations, such as the water temperature, the ambient temperature, and the temperature of the stove surface. An Arduino Uno was used as the microcontroller for these sensors. The WBT sensor setup could not replicate the pollution sensing setup from D-Lab's Burn Lab, since that relies on extracting a sample from the exhaust of a fume hood, but ambient pollution data from the Sensen dataloggers were used during analysis of the WBTs.

Frequently, only one WBT was performed on each stove, due to constraints on the length of time for which the team could use a family's stove. It was also difficult to control for variables between households such as firewood species, wood moisture level, pot size, and pot material, since the team used the fuels and utensils locally available. As a result, it is not possible to draw statistically significant conclusions from the WBT data due to the lack of repeated trials, but the data still offer valuable insights.

Kitchen performance tests (KPTs) were also performed in two locations in Kyanjin Gompa. A set amount of wood was weighed at the start and end of the team's three-day stay in the town, in order to to determine the rate of daily wood use for cooking and heating [51].

4.2 Location-Specific Survey Results

4.2.1 Kyanjin Gompa, Nepal

Kyanjin Gompa, shown in Figure 4-3, is located in northern Nepal in Bagmati Province. It is a remote village, located a two-to-three day walk up the Langtang Valley from the nearest vehicle-accessible town, which is itself a day's drive from Kathmandu. Kyanjin Gompa lies at a high elevation of 3900 meters, and is a popular tourist destination for trekking and mountain climbing in the warmer months. Much of the town's income is derived from tourism, and many of the buildings in the town are guest houses. Residents also raise animals, especially yaks, as a source of income. Temperatures in Kyanjin Gompa are slightly above freezing during the day during the winter, and are below freezing at night. In the summer, average temperatures are around 12°C, with a rainy season in July and August [52]. The area was greatly affected by 2015 Nepal earthquake. The nearby town of Langtang was destroyed in an avalanche during the earthquake, leading to 300 deaths, including those of many family members of Kyanjin Gompa residents.

It is difficult to transport goods and construction materials to Kyanjin Gompa, and supplies are usually carried up the valley by yaks or mules. The town can also be reached by helicopter, which is occasionally used to import goods. Cooking and heating fuels, including LPG and firewood, are more expensive in Kyanjin Gompa due to the added cost of transportation. While wood is generally freely gathered by communities at lower altitudes, households must pay for wood to be transported up the valley to Kyanjin Gompa.

Figure 4-3: The town of Kyanjin Gompa, Nepal in January. Temperatures are below freezing in winter, increasing the need for space heating.

All households surveyed in Kyanjin Gompa had open fires or metallic biomass-burning stoves, which provide more heat in the cold climate. The lack of clay stoves can also be attributed to the lack of available material; clay can be found along the banks of the river that runs through the valley, but the walk to the river is far and the ground is frozen in winter. The main fuels for cooking and space heating in Kyanjin Gompa were yak dung and firewood, and the primary firewood species were rhodedendron and Himalayan birch.

Five households were surveyed in Kyanjin Gompa. Four of the households, three guest houses and a local bank with an attached kitchen and living quarters, were modern houses with concrete walls and wood floors. The modern houses had large metallic stoves of the same design, which were imported from Tibet as aid after the 2015 earthquake. Figure 4-4 shows one of these metallic stoves.

The metallic stove had three pot holes; the primary pot hole was located directly above the firebox, with two smaller pot holes farther back in the stove. Metal rings could be used to adjust the size of the pot holes, and the pot holes could also be fully closed by placing a metal plate atop it. The stove included a chimney, and many kitchens were also fitted with a ceiling-mounted hood that was installed above the stove. The design also included a grate below the firebox, with an ashtray located beneath the grate. A warm storage chamber was located towards the back of the stove; in the guest house where the team stayed, this box was used to store pine needles, which were dried and burned as incense for religious purposes. The firebox had a door that could be opened and closed.

Figure 4-4: The large metallic stove found in many of Kyanjin Gompa's guest houses and the local bank.

The modern houses were generally satisfied with their metallic stoves, although one household complained about the stove's fuel inlet being too small. The guest houses and the bank reported using their stoves for cooking for an average of 6 hours each day, and multiple households stated that they liked the space heating provided by their cookstoves.

Though the metallic stoves were not homemade, some households had made modifications to their stoves. For example, the proprietor of the guest house where the team stayed had noticed that the spaces in the grate were far enough apart that hot char would fall into the ashtray, reducing the heat provided by the fire. In response, she had placed a piece of sheet metal over the grate, which prevented char from falling into the ashtray but also reduced the effectiveness of the grate at providing airflow and preventing ash buildup. The proprietor of the guest house had also placed another piece of sheet metal to partition off the section of the firebox beneath the secondary pot holes, as she primarily used the front pot hole for cooking. The metal sheet was made so that if carefully placed, it would not block the airflow route to the chimney.

The manufactured metallic stoves were also more difficult to maintain. The employees in residence at the local bank had a hole in their stove's chimney, but lacked the proper tools and materials to fix the issue. They had covered the hole with sheet metal, but some smoke still came though, and they hoped that the team could devise a better way to maintain the metallic stoves on a future visit.

The modern kitchens also had LPG stoves, which were mainly used for making tea and snacks. Some guest houses had a solar-powered water heating system installed. All houses surveyed had electric lighting, and electricity was subsidized for low-income households. The guest houses also had separate heating stoves located in the combined dining area and living room, which were also made from sheet metal and burned firewood and yak dung. The heating stoves were fired for an average of 6 hours a day.

The fifth survey in Kyanjin Gompa was conducted at the home of an older man, who cooked on an open fire shown in Figure 4-5(a). He lived in a one-room home with walls of corrugated sheet metal and a dirt floor, and reported using his stove for 2 to 3 hours a day. The man stated that he wanted to purchase an improved stove, but lacked the money to do so.

All surveyed households reported burning more fuel in the winter months due to the increased need for space heating. One guest house reported high levels of smoke during the rainy season in June and July. Other modern houses did not report pollution issues, and the older man with the open fire said that pollution was a problem all year round.

Most households purchased firewood once or twice a year, as opposed to regularly gathering wood on a daily or weekly basis as is common at lower elevations. Wood collection trips took an average of 6 hours. Firewood was either stored inside the home or in a woodshed adjacent to the home. The average wood moisture content at the surveyed households was 9%. All households reported cooking once in the morning and once in the evening. Many households used a metal tube to help with lighting and maintaining the fire. The cook would use the tube to blow air into the fire, allowing finer control over the location of air injection.

In addition to the surveys, ambient household data were collected at the guest house where the team was staying and the local bank, and two water boiling tests were performed at the team's guest house. Kitchen performance tests were also conducted at the team's guest house and the local bank. At the local bank, 19.4 kg of wood was used over the course of two days for four residents, resulting in 2.4 kg of wood per capita per day. For the guest house, 36.8 kg of wood was used over two days for the guest house proprietor and nine guests, resulting in 1.8 kg per capita per day.

(a) (b)

Figure 4-5: An open fire in a residence in Kyanjin Gompa (a), and metallic stoves in Kyanjin Gompa's community housing for older residents (b). Both rooms were very smoky.

In addition to the households where surveys were conducted, the team also visited a community housing block in Kyanjin Gompa for elderly residents who live alone. These people were not surveyed due to a language barrier; some of the older residents only spoke Tibetan, which was not spoken by anyone on the team. The community housing project had provided smaller metallic stoves. These stoves were lower to the ground compared to the metallic stoves in the modern houses, and they had two pot holes and a chimney. These stoves are shown in Figure 4-5(b).

The community housing stoves' chimneys were not easily accessible for maintenance. Many of the chimneys had become clogged, and there was a backdraft of smoke into the house. Some of the fireboxes sloped down from the entrance and were full of ash, hindering airflow to the fire, which may have contributed to the smokiness of the stoves. Firewood needed to be cut down into smaller pieces to fit in the firebox inlet, a task that was difficult for some of the elderly women. Some of the community housing residents had also modified their stoves; they rarely used the secondary pot hole, and some of them had blocked off that portion of the firebox with rocks and pieces of sheet metal. This had the additional effect of blocking some of the airflow to the chimney, which could be another reason for the backdraft of smoke into the room.

Since maintenance proved to be an issue for many manufactured stoves, it is recommended that the team bring tools and materials to maintain and fix stoves for the next field visit. It was also noted that the firebox of metallic stoves was frequently much larger than the fire, which may reduce the stoves' cooking efficiency. The modification of metallic stoves was prevalent, demonstrating that stoves purchased or provided to households are not necessarily the best fit for their needs. In the future, the team could consider holding a workshop to help households improve their stoves without negatively affecting the stoves' performance.

4.2.2 Langtang Valley, Nepal

In order to reach Kyanjin Gompa, the team trekked along the Langtang Valley. The trail up the valley began at the town of Syapru Besi at an altitude of 1500 meters, and ascended to 3900 meters. Between Syapru Besi and the high-altitude villages of Langtang and Kyanjin Gompa, many households were guest houses located along the valley. The landscape and climate varied along the length of the valley; the lower part of the valley was forested, but vegetation was limited to grasses and shrubs at higher altitudes. In Kyanjin Gompa at the end of the valley, temperatures averaged 12°C in the summer and slightly below freezing in the winter [52]. In Syapru Besi at the mouth of the valley, summer temperatures averaged 25°C and winter temperatures averaged

10°C [53]. Three surveys were performed in the Langtang Valley at guest houses at elevations of 2400, 2500, and 3400 meters. The team also observed the cookstoves of additional guest houses as we passed through the valley, and a water boiling test was performed on a clay stove at the guest house at 2500 meters of elevation.

The guest houses in the Langtang Valley used large cookstoves that could accommodate many travelers. All guest houses cooked with firewood and yak dung on biomass stoves, and most guest houses also had LPG stoves. LPG was more expensive to obtain at high altitudes, and higher-altitude guest houses reported needing to pay for transportation of firewood up the valley. The average wood moisture content at the Langtang Valley households was 11%. Some guest houses, especially those at higher altitudes, also had solar-powered water heating. All guest houses had electric lighting, which were provided partially through solar panels. The lower part of the valley was served by the electrical grid and the upper part by a hydroelectric plant, with a gap inbetween. Electrical transmission lines in the valley could be unreliable. The guest houses reported cooking once in the morning and once in the evening, with cookstoves being fired for an average of 6 hours per day.

The material and design of the guest house's cookstoves changed with the altitude. Below 3000 meters, large homemade clay stoves were used, as seen in Figure 4-6(a). These stoves were raised off the floor and could be tended while sitting on a stool or bench in front of the fire. The clay stoves had multiple pot holes, with the configuration differing between households. Some stoves had clay bumps around the pot holes, or metal pot stands packed into the clay, to create a gap between the pot and the clay.

The size of the stoves allowed for larger pieces of firewood to be burned. The larger stove also led to more vertical space in the firebox, providing more room for the combustible gases released from the firewood to rise, mix with air, and further burn. The taller combustion chamber is similar to the design of rocket stoves, a common style of improved biomass cookstove [34]. Increasing the height of the stove could be a potential avenue of improvement for smaller clay stoves.

Most clay stoves had a chimney, or simply a hood or opening above the stove that led to the house's attic, which then vented smoke outside. Frequently, households used the chimney hood for smoking or preserving meat. A few of the chimneys had coupled metallic water heaters, but none of the water heaters were in use; households complained that the metal would rust and contaminate the water, and that the water would sometimes overheat, boil, and create unwanted steam. A potential solution to increase household energy efficiency is an improved water heater, or heating another thermal mass attached to the chimney to reduce heat loss through chimney exhaust.

(a) (b)

Figure 4-6: A typical large clay guest house cookstove (a) and a common metallic heating stove found at guest houses (b) in the Langtang Valley. A pot of water is warming on top of the heating stove.

At higher altitudes, above 3000 meters, guest houses instead used metallic stoves. Some of those cookstoves were the same style as the large metallic stoves found in Kyanjin Gompa, shown in Figure 4-4, which were imported from Tibet as aid after the 2015 Nepal earthquake.

The guest houses all had a separate living and dining room with a dedicated heating stove. The heating stoves were made from metal, and many were purchased from the same supplier and alike in design. Firewood and yak dung were used as fuels in the heating stoves, and the stoves were also used for water heating, as seen in Figure 4-6(b). The surveyed households reported larger amounts of fuel use in the winter. The heating stoves had chimneys, which usually vented into the same attic space as the kitchen chimney or smoke hood.

4.2.3 Salambu, Nepal

Salambu, shown in Figure 4-7, is a village located in east-central Nepal in Kavrepalanchok District at an elevation of 1600 meters. It is located 40 km and 4 hours from Kathmandu, and the village is somewhat remote due to poorly-maintained roads through mountainous terrain, which are especially difficult to navigate during the rainy reason [54]. Salambu has an approximate population of 1000 people, most of whom rely on agriculture and animal husbandry for income [55], [56]. The village has a humid subtropical climate with a rainy season lasting from June through August; temperatures average 26°C in summer and 15°C in winter [57].

Figure 4-7: The town of Salambu, Nepal, in the foothills of the Himalaya.

Kathmandu University and D-Lab have collaborated with Salambu on multiple projects involving household energy and clean cooking in the past. KU's Dhulikhel Hospital has an outreach clinic in Salambu; in 2013 and 2014, the hospital conducted a program that introduced improved cookstoves to many households. Previous surveys regarding household energy were conducted in Salambu by D-Lab in 2016, and a study was performed on household air pollution levels and personal pollutant exposure levels in 2017. Additional surveys evaluating the community's use and perception of the improved cookstoves were conducted in 2019 [56]. The D-Lab team also visited Salambu in January 2022 and surveyed nine households, collected ambient condition data in three households for three days, and conducted water boiling tests on a traditional cookstove and an improved cookstove.

Surveys in 2019 reported that 98% of households in Salambu primarily use biomass fuels for cooking. Some households purchased firewood from a community forest, and some collected firewood from their own trees for free. Residents have reported a shortage of firewood in recent years, due to increases in the price of wood from the community forest. However, firewood is still far less expensive and more accessible than alternate cooking fuel sources [55].

Families surveyed in 2022 reported that they used 3 to 20 kg of firewood a day and cook 2 or 3 times a day, spending an average of 3 hours on cooking per day. Households collect firewood once or twice a month, which took an average of 3 hours. Common species of firewood included pine, alder, and sal wood. Measurements of wood moisture in January 2022 found an average moisture content of 14%.

Households in Salambu also use firewood for space heating, and most families' only source of heat is from kitchen cookstoves [55]. In surveys performed in 2016, all households reported feeling cold in December and January, and two-thirds of households reported feeling cold in November and February. Households in Salambu reported higher amounts of fuel use in the winter.

24% of households had access to LPG, but rarely used it due to the high cost and difficulty of access [56]. LPG can be purchased from the nearest town of Banepa, which is accessible via bus. More modern houses in Salambu are built from concrete and cement; older houses and structures are made from wood, clay, or corrugated sheet metal. Many houses were damaged in the 2015 Nepal earthquake and rebuilt afterwards; these more modern houses are more likely to use LPG as the cooking fuel. Houses in Salambu have grid electricity for lighting, and a small number of households have electric stoves, but the grid can be unreliable due to occasional issues with transmission lines [55].

Surveys in 2016 found that traditional cookstoves in Salambu are mainly three-stone fires, three-leg metal stoves, and homemade clay stoves without a chimney. Figure 4-8(a) shows a traditional clay U-shaped cookstove. Many households also had an improved cookstove, which either took the form of a clay stove with a chimney or a cylindrical sheet-metal stove. Between 50% and 60% of households in Salambu had both improved and traditional stoves [56]. Many households had a traditional cookstove outdoors to prepare animal feed, and an improved cookstove indoors to cook for the family.

The improved clay cookstoves were introduced through a program run by Dhulikhel Hospital in 2013 and 2014. Most of the improved cookstoves are of a design developed by the Nepalese government, shown in Figure 4-8(b). These stoves were built by professionals from Kathmandu, and occasionally maintained by the same personnel. Some improved stoves were also homemade in a similar style to the professionally made stoves.

(a) (b)

Figure 4-8: A traditional clay cookstove, built into the wall of the kitchen (a), and a professionally built improved cookstove (b) in Salambu.

The professionally built improved cookstoves are made with molded clay bricks, with another layer of clay spread over the surface. The design features two pot holes with the firebox directly under the primary pot hole, as well as a chimney. The chimney exhaust exits sideways through the houses' walls, offering easier maintenance due to the chimney not extending up to the roof. The exit of the chimney is usually reinforced by a cylindrical roll of sheet metal or a repurposed metal can. For chimney maintenance, a hole is located on the side or on top of the chimney. Households reported that the holes for chimney maintenance release a small amount of smoke into the home, but not enough to pose an issue. A study in 2017 determined that the improved stoves lowered exposure levels to particulate matter and carbon monoxide by more than 50%, but even with the improved stoves, a study in 2017 found that household pollution levels were still eight times higher than the World Health Organization's recommended maximum [56].

Despite the installation of improved cookstoves, focus group discussions and semi-structured interviews in 2019 revealed that some households still prefer traditional cookstoves. In 2019, 69% of households' primary stove was a traditional cookstove [55]. The traditional stove was viewed as fast and convenient, despite the high levels of smoke and relatively higher fuel use. In comparison, the improved stoves cooked slower and needed more maintenance, but resulted in less smoke and less fuel use. Many families also reported that the improved stove required firewood to be chopped into small pieces, a time-consuming task that discouraged use of the stove [55], [56]. Survey respondents acknowledged that LPG stoves eliminated smoke, but noted its downsides of high cost, slow cooking, and worse-tasting food [56]. The 2022 surveys yielded similar responses regarding opinions on stoves: generally, households like the low cost and the taste of food from clay stoves, but wished that their stoves produced less smoke. Households with improved cookstoves surveyed in 2022 were generally satisfied with their cookstoves.

4.2.4 Uttarkashi, Agoda, and Dehradun, India

In India, the team visited a few locations in the state of Uttarakhand, including the town of Uttarkashi, the village of Agoda, and the region's capital city of Dehradun, which has a population of near 1 million. In Uttarkashi and Agoda, data were collected on households' ambient temperature, humidity, and pollution levels. In Agoda and Dehradun, water boiling tests were performed on local stoves.

Uttarkashi is a large town of 40,000 residents located at an elevation of 1200 meters, shown in Figure 4-9(a). Uttarkashi is on the road from Dehradun to Gangotri, the headwaters of the Ganges River, and is therefore a popular tourist destination in the warmer months. Summer temperatures average 20°C in Uttarkashi, and winter temperatures average 5°C [58]. Two households were surveyed in Uttarakashi, and household condition data were collected at one of the houses for two days.

(a) (b)

Figure 4-9: The town of Uttarkashi (a), and a traditional clay stove in an Uttarkashi household (b).

Both surveyed households in Uttarkashi had traditional homemade clay stoves without chimneys as shown in Figure 4-9(b), and used firewood for fuel. The households collected wood from nearby forests for free every day or every few days. Wood collection involved a 5 km walk and took an average of 4 hours per trip, and wood moisture content averaged 25%. Both houses also had LPG stoves, but they were used much less often. The households cooked twice per day, once in the morning and once at night, for an average stove use of 4 hours per day. The households' kitchens were separate buildings from the main house. For space heating, both households used hot coals and char from the stove, which were carried into the main house after cooking was finished. Cooks in both households reported eye irritation issues, and also reported increased pollution levels and increased fuel use in winter. The surveyed Uttarkashi households were older homes on the outskirts of the city. The team was told by our local contact in Uttarkashi that more modern houses used LPG stoves for cooking and firewood for heating with metallic space heating stoves.

Agoda, shown in Figure 4-10 (a), is a small village at 2200 meters of elevation half a day's drive into the mountains from Uttarkashi. A few hundred people reside in the village, and the community relies on agriculture and animal husbandry for income. Four households were surveyed in Agoda, and ambient household condition data were collected for one household.

(a) (b)

Figure 4-10: The village of Agoda (a), and a traditional clay stove in an Agoda household (b).

Agoda households had homemade traditional clay stoves, often located in a separate kitchen. Firewood was the primary cooking fuel; households used roughly 20 kg of firewood per day in winter and roughly 10 kg per day in summer. Firewood was collected every few days from the local forest, which took an average of 5 hours per trip. Wood moisture levels were found to be around 17%. Some households also had LPG stoves, and electricity was used for lighting. Families used their stoves in the morning and evening, for an average of 3 hours per day. Maintenance was performed on cookstoves every month or few months to repair cracks. Space heating was achieved by carrying hot coals from the separate kitchen building to the main house.

Residents complained about the smoke from heating and cooking, which led to eye irritation and coughing.

One water boiling test was performed on a traditional clay stove in Agoda, which is shown in Figure 4-10 (b). The firebox of the stove was lower than the floor, which served to contain ash and char, but impeded airflow into the fire. The room was very smoky during the test; there was a window above the stove, but a lot of smoke did not escape through the window due to the unfavorable wind direction.

In Dehradun, a series of water boiling tests was performed on a traditional clay stove at a local resident's house near UPES, shown in Figure 4-11(a). The stove was a U-shaped clay extrusion, with three lumps of clay as pot stands. The results of these tests are detailed in Section 4.3.


(a) (b)

Figure 4-11: The indoor (a) and outdoor (b) traditional clay stoves in a Dehradun household.

The clay stove in Dehradun was located in a separate kitchen apart from the main house. The main house had a modern kitchen with LPG fuel that was used for most cooking, but the firewood-fueled clay stove was used for water heating and preparing animal feed, which are longer cooking processes. The household also had an outdoor traditional clay stove, shown in Figure 4-11(b), which was used in all but the rainy season. Dehradun has average temperatures of 28°C in the summer and 10°C in winter; the warmer weather allows for more outdoor cooking [59].

The household in Dehradun was not formally surveyed, but the team talked with the family about cooking practices in the region. In less mountainous areas such as Dehradun, households typically have more space, allowing families to have multiple clay stoves. The LPG distribution network is also better in lowland areas.

4.2.5 Chakrata, India

For the past few years, one of D-Lab's partner universities, the University of Energy and Petroleum Studies (UPES) in Dehradun, has been working closely with the villages of Koruwa, Jadi, and Mangrauli in the subdistrict of Chakrata. Chakrata is located in the state of Uttarakhand roughly 90 km from Dehradun, and the villages are accessible by car. Each village has a population of 400 to 500 people, and the villages' primary sources of income are agriculture of cash crops and dairy farming. The villages are located at altitudes of between 1600 meters and 2200 meters, in the foothills of the Himalaya. Temperatures in Chakrata range from highs of 31°C in summer to lows of 5°C on winter nights. The area has a humid subtropical climate, with the rainy season lasting from mid-June to mid-September. The region sees snowfall in the winter [60], [61].

The D-Lab team was not able to visit Chakrata in January 2022 due to the COVID-19 pandemic, but D-Lab and UPES's joint findings on household energy in the area are presented here. Surveys of 15 households in the three villages were conducted in December 2020 by researchers at UPES, and the UPES team also collected household ambient data for nearly three months using Sensen sensors in the fall and winter of 2021.

All surveyed households used wood as their primary cooking fuel, and the firewood was gathered from local forests for free. Crop residues were also sometimes used as a biomass fuel. In addition to firewood, 73% of surveyed households had access to LPG as a cooking fuel. However, LPG usage was limited to making tea or cooking small meals, due to its high cost and the travel needed to obtain fuel refills. 27% of households had an induction stove, but those were also not commonly used [60], [61].

All households had homemade traditional clay stoves, with either two or three pot openings, as shown in Figure 4-12. The D-Lab model stove described in Chapter 3 was based on these stoves. The stoves generally did not have chimneys, but many houses had a hole in the roof above the stove to vent pollution outside; this hole could be covered with a stone slab when unused. Most Chakrata households had their kitchen in a separate room, but not a separate building, from the living area. The stoves were built upon a stone or brick foundation on the floor of the house. In addition to the clay that made up the main body of the stove, other locally-gathered construction materials included grass, starch, cow dung, and goat hair. Cow urine was regularly applied to the stove, both as a disinfectant and for ritual purposes. The stoves was repaired every four to five months, and a new stove was constructed every two to three years. A new stove was sometimes constructed as part of festivals. The stove was constructed and maintained by the women of the household [60], [61].

Figure 4-12: A three-pot clay stove in Chakrata operated with firewood. The D-lab model cookstove was based on the design of Chakrata stoves.

In the winter, the cookstoves are also used for space heating. The households keep the stove burning after cooking in the winter months, and as a result, residents reported higher fuel use and higher pollution levels during winter. The survey respondents stated that the advantages of traditional clay stoves included the low cost of fuel and materials, the dual heating and cooking capability, and that the stoves resulted in better-tasting food and allowed for a broader range of foodstuffs to be cooked. All households listed smoke as a negative trait of their cooking setups, and many commented on the issues of high wood use, long cooking times, and excessive heat in summer [60], [61].

In addition to the surveys, data on household ambient conditions were collected between October and December 2021 in two households. The data were collected using Sensen sensors, which recorded temperature, humidity, and concentrations of CO, CO_2, PM 2.5, and PM 10. For one of the two houses, one sensor was placed in the living room and one was placed in the kitchen; the second house only had a sensor in the kitchen. Figures 4-13 and 4-14 show a sampling of the collected data across four days in early November.

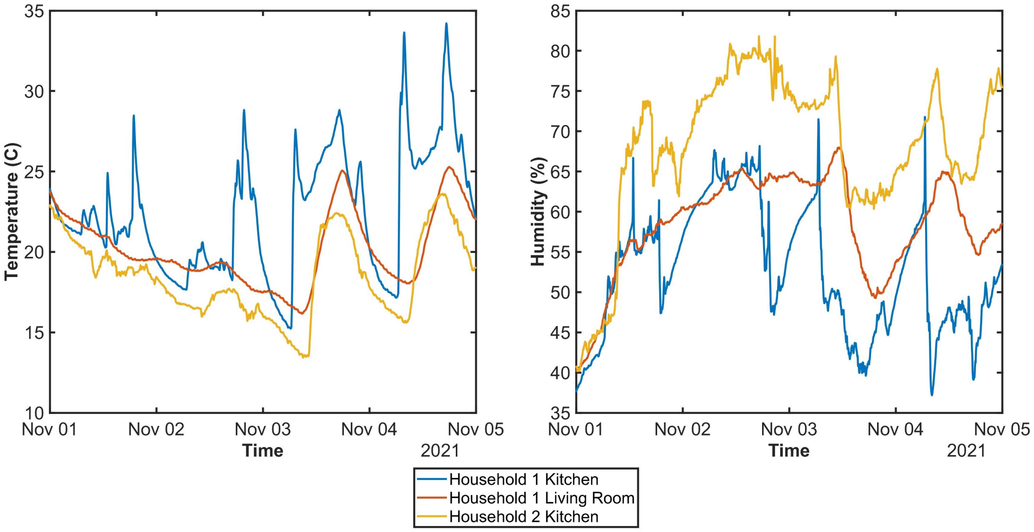


Figure 4-13: The temperatures and humidities in two Chakrata households over the course of four days in early November.

It can be seen in Figure 4-13 that each household fires the stove a few times throughout the day, corresponding to the increases in indoor temperature. When the temperature increases in the homes, the humidity also decreases. For both households, the exact schedule of stove use is inconsistent among the different days. The living room is colder than the kitchen in the first household, and there appears to be a delay in heat transfer between the kitchen and living room. The second household is colder and more humid than the first.

Figure 4-14 shows spikes in pollution levels as the cookstoves are fired. Pollution levels peak at different times in the two households, due to the stove being fired at different times. Within the first household, the living room has lower levels of pollutants compared to the kitchen. Carbon dioxide levels in the living room of the first household seem to be driven by human occupation, since they are higher at night when the family is present within the house. The second household has slightly less pollution than the first, though pollution levels are high in both houses.

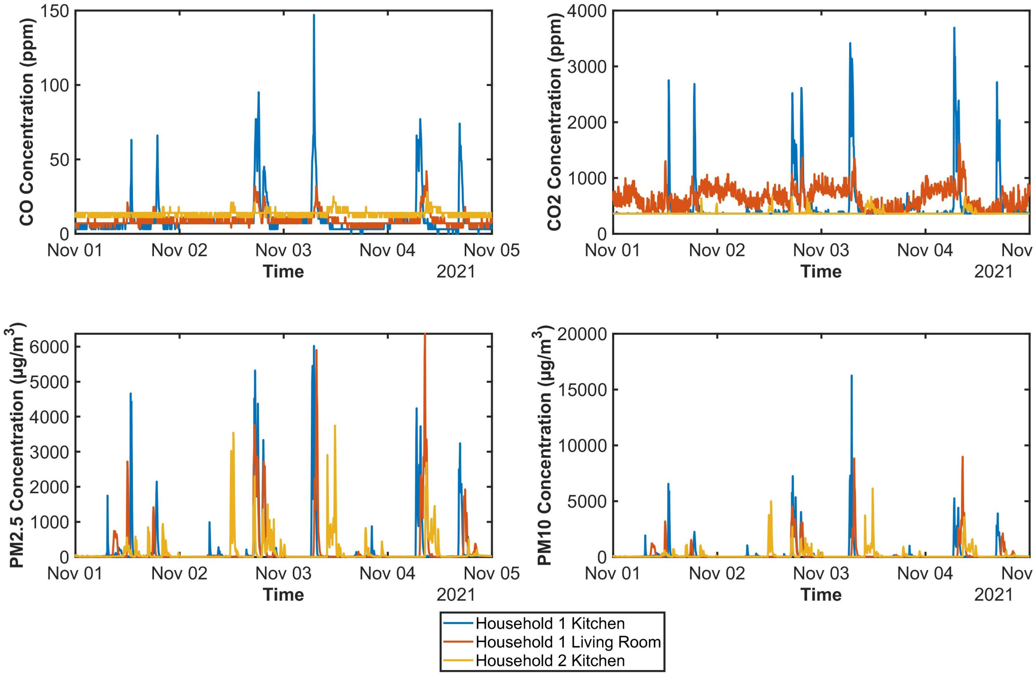


Figure 4-14: Pollutant levels in Chakrata households over the course of four days in early November.

Figure 4-15 shows the differences in various household ambient conditions across the three months when the data were taken. Temperature and humidity both decrease as fall progresses into winter, which is colder and drier. Average pollutant concentrations generally increase as weather gets colder. The exception to this are the carbon monoxide levels in the second household, and the carbon dioxide levels in the second household's kitchen and the first household's living room. The carbon dioxide levels may remain the same in those locations because they are primarily driven by human occupation. The daily maximum levels of pollutants do not change significantly between the different months. Another metric considered was the daily hours with high levels of PM 2.5 and PM 10, which were considered to be above the thresholds of 35

$\mu g/m^3$ and 70 $\mu g/m^3$ respectively, in accordance with the interim targets set by the World Health Organization [11]. The daily hours with high particulate matter levels also increased into winter, slightly in November and more significantly in December. Overall, PM 2.5 and PM 10 levels are two to three orders of magnitude higher than the WHO targets, and CO levels are within one order of magnitude of the targets [11]. The statistics depicted in Figure 4-15 can be found in Appendix E.

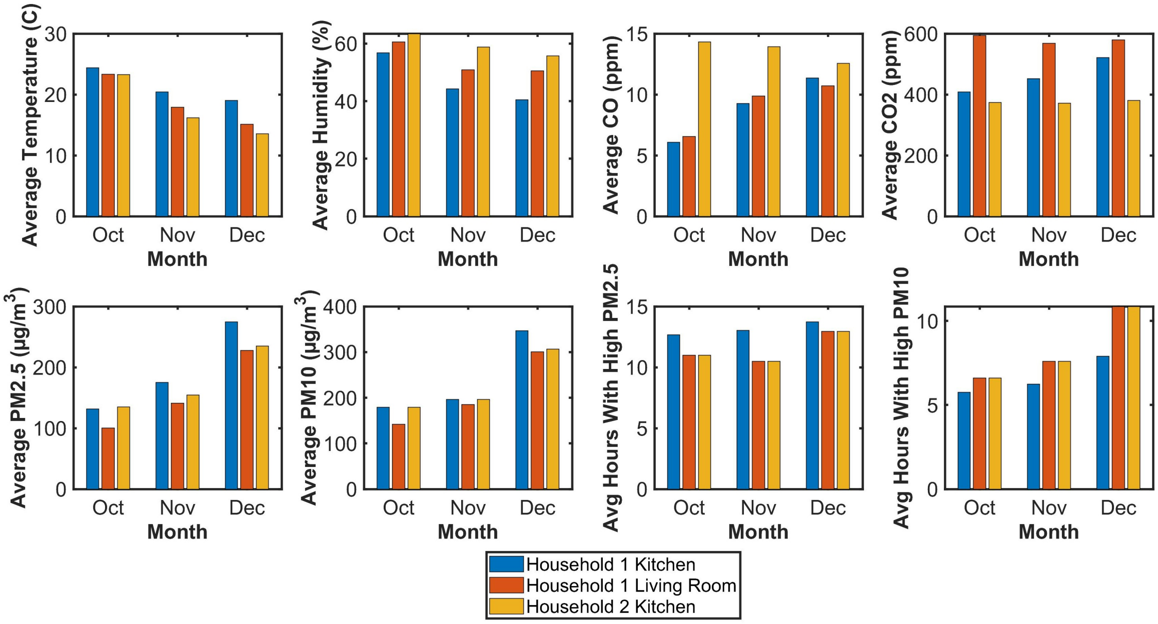


Figure 4-15: Average temperatures, humidities, and pollutant levels for the months of October, November, and December in Chakrata.

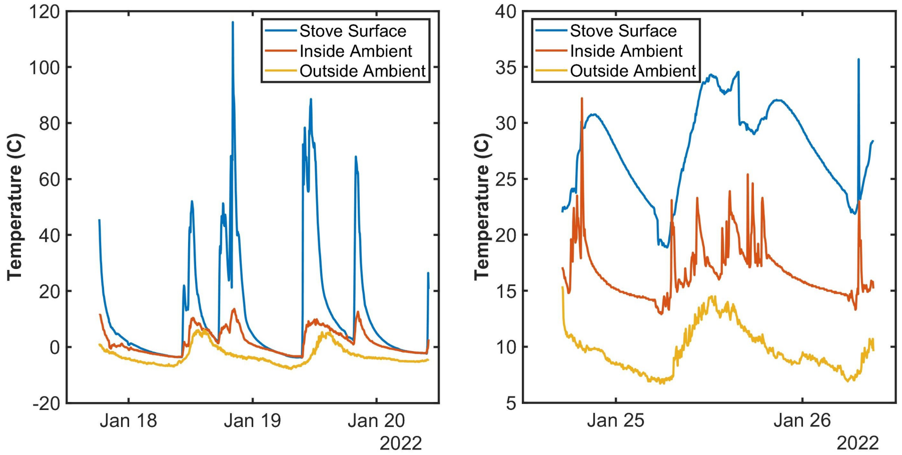
From these data, it can be concluded that household air pollution is partially driven by heating needs, since pollution levels clearly increase as the weather gets colder. As a result, solutions to reduce household air pollution in the Himalaya should focus on both clean cooking and clean heating. Further study is needed to determine whether the increased household air pollution levels are due to additional smoke being generated from larger quantities of fuel burned or due to poorer household ventilation in the winter, or whether both factors play an equal role.

4.3 Experimental Findings in the Field

4.3.1 Ambient Household Conditions

At each of the towns and villages the team visited, data were collected on indoor and outdoor temperature and humidity, stove surface temperature, and levels of CO, CO_2, PM2.5, and PM10. The sensors used to collect these data are described in more detail in Section 4.1, and their manufacturers and models are listed in Appendix A. This section presents indoor and outdoor temperature profiles, average temperature and pollution levels, and analyses of overnight household cooling and stove space heating for each of the locations visited.

Figure 4-16 shows sample data for indoor temperature, outdoor temperature, and stove surface temperature for (a) a kitchen with a metallic stove in Kyanjin Gompa and (b) a kitchen with an improved clay stove in Salambu. For all locations where data were taken, the increases in indoor temperature primarily corresponded to the firing of the stove, indicated by the increase of the stove surface temperature. At all locations, temperature and humidity were inversely correlated, agreeing with the data collected in Chakrata described in Section 4.2.5.



(a)

(b)

Figure 4-16: The indoor, outdoor, and stove surface temperatures of a kitchen with a metallic stove in Kyanjin Gompa (a) and a kitchen with an improved clay stove in Salambu (b).

There are key differences between the two households in Figure 4-16. Kyanjin Gompa is much colder than Salambu, so the indoor and outdoor temperatures are both much lower. In Kyanjin Gompa, the outdoor temperature shows sharper increases and decreases, due to the strong high-altitude sunlight around midday. In both locations, the indoor temperature decreases along an exponential curve overnight.

Since clay is a better insulator than steel and has a much higher thermal mass, the surface of the Salambu clay stove remains at much lower temperatures compared to the metallic stove. In Kyanjin Gompa, the stove surface temperature decreases along an exponential curve, asymptotically approaching the ambient indoor temperature halfway throughout the night. In Salambu, the stove surface displays a linear cooling reponse, and the stove temperature never drops below the ambient. The difference in stove surface cooling responses may suggest a disparity in cooling mechanisms for metallic and clay stoves. The metallic stove's exponential decrease in temperature aligns with Newton's Law of Cooling, indicating that the body of the stove can be seen as mostly homogeneous in temperature. On the other hand, heat transfer in the clay stove may be dominated by the internal thermal resistance of the large mass of clay, and the larger Biot number makes Newton's Law of Cooling an unsuitable model.

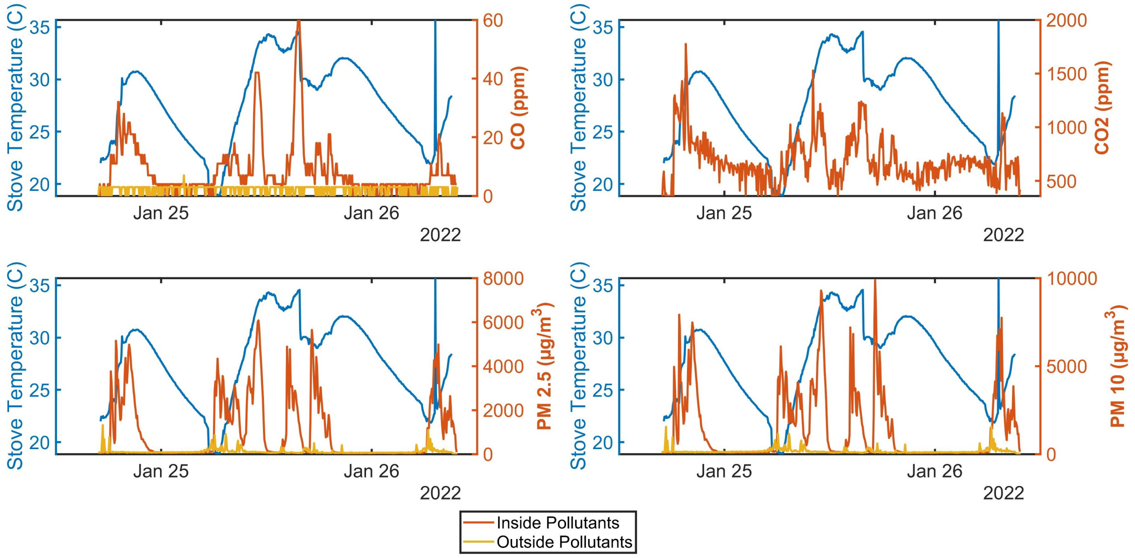


Figure 4-17: Indoor and outdoor pollutant levels at a Salambu household with an improved clay stove.

Figure 4-17 shows the pollution levels at the same Salambu household with the improved cookstove as in Figure 4-16. In all households, spikes in indoor pollution levels corresponded to the firing of the stove. The levels of outdoor pollutants were only measured at this particular household. Even with the pollution sensor placed on a different side of the house than the chimney exhaust pipe, the outdoor PM 2.5 and PM 10 levels increase slightly at the same time that the indoor pollution levels increase. It can be concluded that the chimney exhaust of the improved stove vents particulate matter to the outdoor environment around the house, which may present a concern for outdoor air quality. The outdoor CO_2 level is not displayed due to a sensor error.

High-level statistics from the ambient household sensors for all locations visited in the field are summarized in Table 4.1. For the purposes of categorization, a stove was classified as an improved cookstove (ICS) if it had a chimney, and a traditional cookstove (TCS) if it did not. Some CO_2 levels are not reported due to a calibration error with one of the sensors. Additional household condition data from the field is presented in Appendix E.

Location	**Stove Type**	**Indoor Temp (°C)**	**Outdoor Temp (°C)**	**In-Out ΔT (°C)**	**CO (ppm)**	**CO_2 (ppm)**	**PM2.5 ($\mu g/m^3$)**	**PM10 ($\mu g/m^3$)**
Kyanjin Gompa	Metal ICS	10.0	0.6	9.3	7	-	419	549
Kyanjin Gompa	Metal ICS	1.8	-3.1	5.0	7	-	39	83
Kyanjin Gompa	Open Fire	-0.1	-2.5	2.5	5	-	541	953
Salambu	Clay ICS	13.0	10.1	2.9	-	-	-	-
Salambu	Clay ICS	16.7	9.6	7.0	9	686	1096	1442
Salambu	Clay TCS	11.8	9.5	2.3	6	-	658	920
Uttarkashi	Clay TCS	14.6	8.1	6.5	43	1488	3056	6871
Agoda	Clay TCS	16.1	6.4	9.6	38	1178	2076	3207

Table 4.1: Statistics describing the average household ambient conditions in the Himalayan villages that the team visited.

The average indoor temperature for all households fell below the World Health Organization's recommendation of 18°C [62]. Indoor temperatures are generally colder where the outdoor temperature is colder, although the average difference between the temperatures ranges from 2 to 10°C.

On average, the presence of a chimney decreases pollutant levels, although households with chimneys still see significant household air pollution. Pollutant levels also varied within the categories of improved and traditional stoves; the improved clay stove in Salambu had higher pollution levels compared to the improved metallic stove in Kyanjin Gompa. The open fire had lower pollutant levels than some of the clay stoves, though this could be due to the high draftiness of the house with the open fire. Particulate matter levels for all households were still far above the WHO standards, although some households had CO levels on par with the WHO's interim targets [11].

The data from Chakrata presented in Section 4.2.5 show that within the same household, colder weather corresponds to higher levels of household air pollution. In order to determine whether or not pollution levels in different households were at all dependent on the local climate, various pollution levels in the visited households were plotted against average outdoor temperatures in Figure 4-18. There appears to be no clear correlation between the two variables, and pollution levels instead seem more dependent on the presence of absence of a chimney.

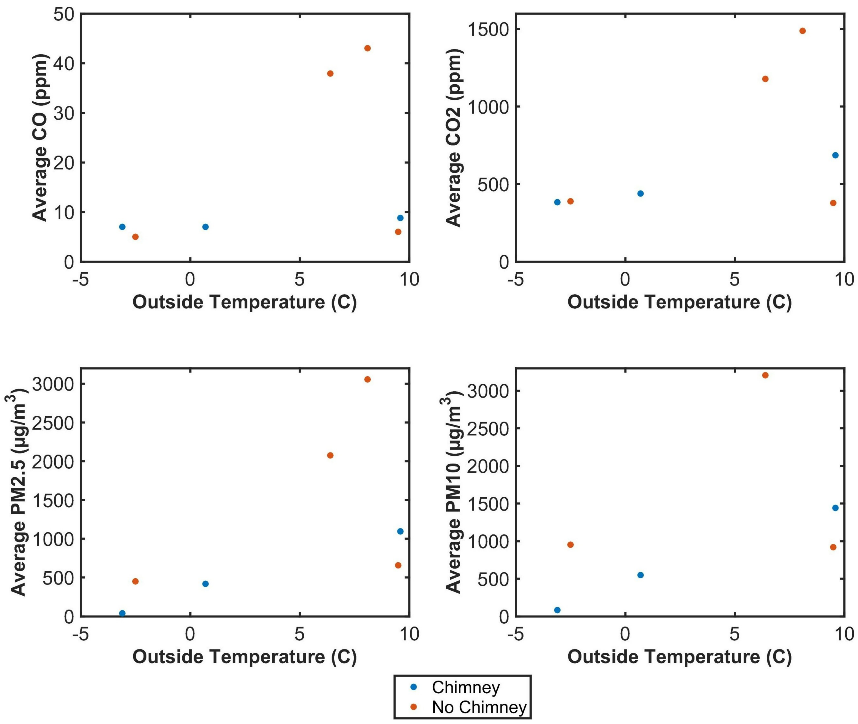


Figure 4-18: Household pollution levels graphed against average outdoor temperatures for the locations visited in the field.

The cooling profiles and heating responses of the households were also analyzed in more detail. For all households, the indoor temperature overnight saw a decrease that followed an exponential curve, with the temperature falling faster at the beginning of the night and slower at the end of the night as the house cooled down. A sample overnight cooling curve can be seen in Figure 4-19. Assuming that the rate of change of outdoor temperature is negligible compared to the rate of change of indoor temperature, and that the temperature of the indoor kitchen is generally homogeneous, the indoor cooling curve aligns with the trend expected from Newton's Law of Cooling. The time constant τ of the exponential curves, or the time it takes for the temperature to be reduced to 37% of its original value, was found for all households.

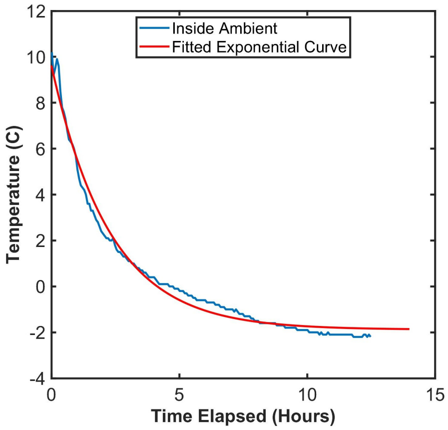


Figure 4-19: The overnight indoor temperature in a Kyanjin Gompa house with an improved metallic stove. An exponential curve fits well to the data.

All houses' indoor temperatures increased linearly when the stoves were fired. To analyze this indoor temperature response, these linear segments were isolated and their average slope calculated for each household. Figure 4-20 shows the extracted portions of data for a kitchen in Kyanjin Gompa.

Table 4.2 shows the average overnight cooling time constants and daytime heating rates for each of the locations where ambient data were collected. The exponential time constants all fell within the same order of magnitude, but it can be seen that houses with an improved stove generally had shorter time constants. This trend is suspected to be caused by chimneys increasing the draft of air through the household, leading to faster cooling. The average heating rates of all households fell between 0.1

and 0.4°C per minute. It was also noted that even within the same house, these parameters differed between individual heating and cooling events.

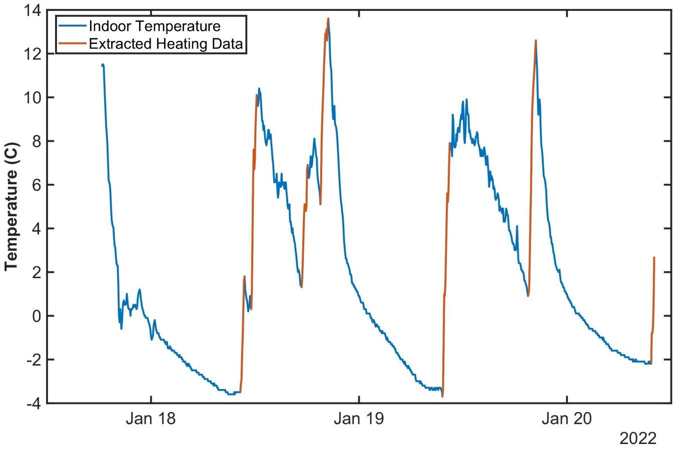


Figure 4-20: The sections of heating data extracted from the indoor temperature profile of a house in Kyanjin Gompa, highlighted in red.

Location	**Stove Type**	**Cooling Time Constant τ (hr)**	**Heating Rate (°C/min)**
Kyanjin Gompa	Metal ICS	2.32	0.19
Kyanjin Gompa	Metal ICS	2.35	0.21
Kyanjin Gompa	Open Fire	3.93	0.26
Salambu	Clay ICS	1.99	0.12
Salambu	Clay ICS	2.86	0.37
Salambu	Clay TCS	2.76	0.15
Uttarkashi	Clay TCS	5.38	0.18
Agoda	Clay TCS	4.11	0.29

Table 4.2: The exponential time constant of overnight cooling trends and the room heating rates when stoves are fired for all locations visited in the field.

The indoor cooling and heating responses can be used as a basis to calculate the heating power provided by the stoves and to model the movement of heat throughout households. However, more information is needed about certain parameters of the kitchen, including the volume of the room, the thermal masses being heated, and the materials and dimensions of household construction materials.

4.3.2 Stove Performance

Water boiling tests (WBTs) were performed at households in the majority of the villages that the team visited in January 2022. The field WBT procedure and the sensors used are described in more detail in Section 4.1. The temperatures of the water, fire, stove surface, and other locations within the stove environment were measured by the portable Burn Lab setup, and pollution levels were taken from Sensen boxes present in the room during the WBTs. The performance parameters of each stove were calculated using the same methods as used in the lab tests, presented in Equations 3.1 through 3.4. The energy contents of different wood species used in the calculations are listed in Appendix B. Statistics from each WBT performed in the field, as well as the average results from the D-Lab model stove under standard conditions, are presented in Tables 4.3, 4.4, and 4.5. Appendix E includes additional statistics from the field WBTs.

Location	**Stove Type**	**Test Duration (min)**	**Fuel Used (kg)**	**Efficiency (%)**	**Firepower (kW)**	**Pot Power (W)**	**Pot Power Ratio (-)**
Kyanjin Gompa	Metal ICS	116.5	2.04	4.32	6.37	275	-
Kyanjin Gompa	Metal ICS	97.1	1.73	5.66	5.63	319	-
Langtang Valley	Clay TCS	27.9	2.24	6.72	23.86	1604	3.58
Salambu	Clay ICS	40.5	1.61	8.70	11.74	1021	2.43
Salambu	Clay TCS	23.3	1.14	7.81	15.58	1216	-
Agoda	Clay TCS	51.1	1.94	5.79	11.28	654	-
Dehradun	Clay TCS	75.9	0.73	13.25	2.87	381	-
Dehradun	Clay TCS	55.5	1.31	7.41	7.08	525	-
D-Lab	Clay TCS	48.0	0.82	13.18	3.67	479	4.07

Table 4.3: Performance parameters for the water boiling tests performed during the field visits.

The thermal efficiencies of the stoves tested in the field ranged from 4% to 13%. Except for the first test on the traditional clay stove in Dehradun, all other tests measured efficiencies below 10%, ranking the stoves at the lowest Tier 0 under the ISO 2018 stove performance standards shown in Figure 3-9 [48]. The metallic stove in Kyanjin Gompa was less efficient at cooking compared to the clay stoves, since much of the energy generated was dissipated to the room as heat, and took a longer period of time to perform the same task. The larger guest house stoves in Kyanjin Gompa and the Langtang Valley used more fuel than smaller stoves for a single household, and there were wide variations in firepower and power into the cooking vessels among the different stoves.

The D-Lab model stove was based on traditional clay stoves from Chakrata, and is discussed in more detail in Section 3.1. The efficiencies of the stoves in the field are almost all lower than the efficiency of the D-Lab model stove, which is likely due to the lab tests being performed under more controlled conditions and using better firestarters and kiln-dried firewood. The lab stove also used less fuel than most of the WBT field tests, and had test durations and fire temperatures comparable to the field data. The pot power ratio of the D-Lab model stove was also similar to those of two-pot stoves tested in the field. Since the team was unable to visit Chakrata in January 2022, it was not possible to compare the lab and field performance of the exact same style of stove. In the future, the team plans to visit Chakrata and perform WBTs there.

Location	**Stove Type**	**Fire Temp (°C)**	**Surface Temp (°C)**	**Avg CO (ppm)**	**Avg CO_2 (ppm)**	**Avg PM2.5** ($\mu g/m^3$)	**Avg PM10** ($\mu g/m^3$)
Kyanjin Gompa	Metal ICS	459	101	4	-	337	392
Kyanjin Gompa	Metal ICS	494	128	6	-	1260	1855
Langtang Valley	Clay TCS	567	17	5	-	291	383
Salambu	Clay ICS	652	47	14	875	2799	4885
Salambu	Clay TCS	608	29	6	-	2673	3574
Agoda	Clay TCS	538	13	61	1931	6249	13645
Dehradun	Clay TCS	460	22	35	1265	3254	5792
Dehradun	Clay TCS	304	20	13	831	3964	6412
D-Lab	Clay TCS	540	-	24	1475	53	-

Table 4.4: Fire temperatures, surface temperatures, and average pollutant levels for the water boiling tests performed during the field visits.

Table 4.4 shows the fire and stove surface temperatures and average pollutant levels for each of the WBTs performed. The metallic stove had much higher surface temperatures for the purpose of space heating; an more accurate assessment of the overall efficiency of the stove should also take into account the useful heating power provided. The fire temperatures did not seem dependent on the type of stove, and it should be noted that the actual flame temperature is likely much higher than the thermocouple measurements. The chimney exhaust temperature was also measured for the improved clay stove in Salambu; the average exhaust temperature was 246°C, showing that a large amount of heat is lost as exhaust in chimneyed stoves.

Emissions factors and emissions rates were calculated for the test results with sufficient pollutant data to perform the carbon balance analysis presented in Equations 3.5 through 3.13. Table 4.5 displays the emissions factors and emissions rates of CO, CO_2, and PM 2.5 for the field WBTs. Using the ISO 2018 stove performance tiers shown in Figure 3-9, all stoves ranked at Tier 0 for CO emissions factors, although the clay stove in Dehradun was close to Tier 1. The PM 2.5 emissions factor level for Tier 1, 1030 mg/MJ, was met by one of the tests on the Dehradun stove but no other test. The D-Lab model stove had lower emissions factors and rates of CO compared to the field test data, but higher emissions of PM 2.5. This difference could be in part due to the different methods of collecting pollution data; the Burn Lab directly measures pollutant levels in a sample of exhaust, but ambient pollutant levels in the houses were instead measured in the field.

Location	**Stove Type**	**CO EF (g/MJ)**	**CO ER (g/min)**	**CO_2 EF (g/MJ)**	**CO_2 ER (g/min)**	**PM2.5 EF (g/MJ)**	**PM2.5 ER (g/min)**
Salambu	Clay ICS	55.7	3.41	938	57.4	11.4	0.699
Agoda	Clay TCS	49.6	1.94	1482	58.2	5.47	0.215
Dehradun	Clay TCS	19.0	0.43	651	14.9	1.58	0.036
Dehradun	Clay TCS	22.4	0.71	1168	36.8	6.19	0.195
D-Lab	Clay TCS	13.9	0.387	717	20.0	28.4	0.801

Table 4.5: Emissions factors and emissions rates of pollutants for the water boiling tests performed during the field visits.

Table 4.6 compares stove performance and pollution levels during the WBTs of stoves with and without chimneys. Kitchens with chimneyed stoves were found to have roughly half the pollution levels of chimneyless stoves. However, PM 2.5 and PM 10 levels were still significant in households with chimneyed stoves, and levels of particulate matter were one to two orders of magnitude above the WHO's accepted thresholds for all stoves [11].

Table 4.6 also shows that among the stoves tested, having an cookstove with an added chimney did not improve thermal efficiency or decrease cooking time. However, there are likely not enough data points to make a meaningful conclusion regarding efficiency; only one clay stove with a chimney was tested, and the data is influenced by the less efficient metallic stove, which had a chimney. The single chimneyed clay stove, shown in Figure 4-8(b), had a higher efficiency than the majority of the traditional stoves tested. On future field visits, more WBTs should be performed on improved clay stoves with chimneys in order to draw more robust conclusions.

Parameter	**Chimney Average**	**No Chimney Average**
Test Duration (min)	84.7	46.7
Fuel Used (kg)	1.79	1.47
Efficiency (%)	6.23	8.20
Average CO (ppm)	8	24
Average PM2.5 ($\mu g/m^3$)	1465	3286
Average PM10 ($\mu g/m^3$)	1936	5961

Table 4.6: Statistics comparing the stove performance metrics and pollution levels during water boiling tests of stoves with and without chimneys.

Figure 4-21 shows the relationships between three key parameters which describe stove performance: fuel use, test duration, and thermal efficiency. Thermal efficiency appears to be negatively correlated to fuel use. Other than for a single outlier, the same is true for thermal efficiency and test duration. However, there is not a clear relationship between test duration and the fuel use. This finding is important to consider when designing improved stoves, since many families see decreasing cooking time as a higher priority than decreasing fuel use, and it is important to note that those two parameters may not be correlated.

In addition to characterizing the stoves in the different villages, the team tested a few simple solutions during the WBTs in Dehradun. On the traditional clay stove in Dehradun shown in Figure 4-11(a), multiple hot start phases were performed for each cold start. On the first day of testing, the second and third hot starts were performed

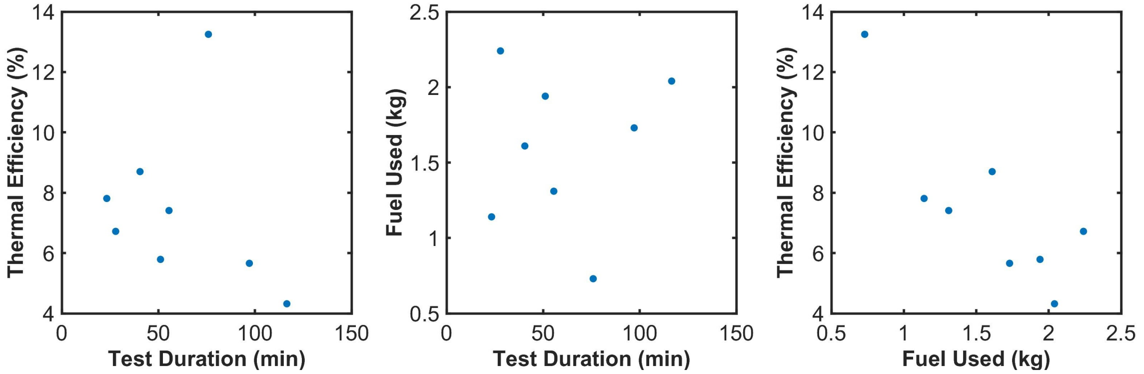


Figure 4-21: Scatter plots showing the relationships between test duration, fuel use, and thermal efficiency among the stoves where water boiling tests were conducted in the field.

with a grate; the third hot start was also performed with the kitchen door closed, since the family sometimes cooked with a closed door. The team also noticed that the firebox extended back beyond the pot, and coals and char would fall to the back of the stove instead of remaining under the pot. On the third hot start of the second day, a piece of brick was added to the back of the stove to keep the heat concentrated under the pot. The results of the Dehradun hot start tests are shown in Table 4.7.

Condition	**Duration (min)**	**Fuel Use (kg)**	**Efficiency (%)**	**Avg CO (ppm)**	**Avg CO_2 (ppm)**	**Avg PM2.5 ($\mu g/m^3$)**	**Avg PM 10 ($\mu g/m^3$)**
Standard	44.7	0.36	10.03	48	1497	4414	8447
Grate	24.8	0.30	15.59	36	1387	3488	5493
Grate, Door Closed	26.3	0.33	14.37	76	2541	5117	1472
Standard	15.9	0.20	23.22	16	1017	3908	5300
Standard	22.5	0.25	19.76	22	852	5555	1256
Smaller Firebox	20.2	0.50	10.04	18	865	4528	9420

Table 4.7: Statistics from the hot start phases of the water boiling tests performed in Dehradun under different conditions.

The performance of the traditional clay stove in Dehradun varied significantly across different tests, with the thermal efficiency of each hot start phase ranging between 10% and 23%. Neither the grate or the brick in the back of the firebox improved the efficiency of the stove, which aligns with the finding that a grate did not improve the efficiency of the D-Lab model stove in lab testing. However, the team noticed that the grate made the fire easier to tend, since there were less concerns about carefully positioning the wood to allow airflow. The closed door noticeably increased the pollution levels in the room.

4.4 Conclusions from Fieldwork

In January 2022, a team from D-Lab visited various towns and villages in north India and Nepal. The team visited a few different communities to survey households, gather data on ambient household conditions, and assess stove performance through water boiling tests. The survey questions focused on fuel collection, cooking, and heating practices. Data-logging sensor systems were used to measure the temperature, humidity, and pollution levels within households.

The primary fuel in all surveyed locations was firewood; yak dung was another common biomass fuel at high elevations in Nepal. In most locations, firewood could be gathered at only the cost of expended time, although households needed to pay for fuel transport in remote, high-altitude areas. Two kitchen performance tests in the town of Kyanjin Gompa in Nepal showed wood use rates of 1.8 kg and 2.4 kg per capita per day. Households reported cooking two or three times a day. In order to maintain the easy accessibility and low cost of biomass fuels, it may be best for clean cooking solutions to take the form of improved biomass stoves.

Households reported more fuel use and higher pollution levels in winter. This survey finding is supported by long-term ambient household condition data collected in Chakrata in north India by D-Lab's university partners at UPES. In Chakrata, household pollution levels increase significantly in winter, suggesting that pollution is partially driven by space heating needs. Improved stove designs should then place equal importance on the functions of cooking and space heating.

The stoves that the team saw varied in design, size, and material. Clay was the most common material for stove construction; some clay stoves had complex designs and included a chimney, and some were simple U-shaped extrusions. At high altitudes, metallic stoves which offered better space capabilities were common. Many houses had LPG stoves but primarily used biomass stoves, aligning with the stove stacking behavior found in other studies about cooking practices in the Himalaya [7], [19], [20]. Some households had an improved clay stove or gas stove in their interior kitchens, but also had an exterior traditional clay stove for heating water or preparing animal feed. During solution design and development, these variations should be kept in mind, as different communities will have different preferences and habits regarding their household energy systems.

House construction materials also varied; the team saw houses and kitchens made of concrete, clay, and corrugated sheet metal. Some households had attached kitchens, and some had kitchens in separate buildings adjacent to the main house. Even within the same town or village, stove designs and household conditions greatly differed. Many guest houses at high elevations had biomass-burning metallic space heating stoves in addition to their cookstoves. Electric lighting was common, but many villages reported unreliable grid connections.

For manufactured stoves, maintenance was a significant issue. Some of the metallic stoves in the high-altitude town of Kyanjin Gompa, Nepal had chimneys were blocked or leaked smoke, and the stoves lacked a way to access the chimneys for maintenance. Households with manufactured stoves were found to frequently modify their stoves to better suit their needs, such as by redistributing the heat between the primary and secondary pot holes. These modifications may also have unintentional side effects which reduce stove performance and increase household air pollution. Going forward, D-Lab and our community partners could design workshops to provide households with knowledge and tools to better modify and maintain non-homemade stoves.

Ambient household condition data were collected in all locations, including indoor and outdoor temperature and humidity, stove surface temperatures, and levels of CO, CO_2, PM 2.5, and PM 10. For all locations, the average indoor temperature fell below the World Health Organization's recommendation of 18°C. The overnight cooling response of indoor temperatures took the form of an exponential curve for all households, with exponential time constants of between 2 and 6 hours. The data suggests that kitchens with chimneys may cool down faster due to the additional draft induced by the chimney. The indoor heating rate when stoves were fired fell between 0.1 and 0.4°C/min for all households. The stove surface cooling response differed based on the stove material, with metallic stove temperatures decreasing exponentially and the temperatures of large clay stoves decreasing linearly.

All households had high levels of indoor air pollution, with levels of PM 2.5 and PM 10 one to two orders of magnitude higher than the World Health Organization's recommendations; the CO levels fell within one order of magnitude [11]. Outdoor pollution levels were only measured at one household, but data suggests that cooking on biomass stoves also leads to slight increases of outdoor pollution levels. Chimneys reduce pollution significantly, but household air pollution levels remain high even with a chimney.

The water boiling tests performed in the field found that stove thermal efficiencies ranged from 4 to 13%. Metallic stoves had a lower cooking efficiency and much higher stove surface temperatures, since they are designed for the dual purpose of space heating. The D-Lab model stove was more efficient than most of the stoves tested in the field and used less fuel, potentially due to the better firestarters and dry fuel used during lab testing. Among the field-tested stoves, thermal efficiency had negative correlations to both test duration and fuel use. A grate in the field on a traditional clay stove did not improve the stove's performance, matching the results from the lab tests discussed in Section 3.3.

For future studies, certain improvements could be made to the field sensors. A limitation of the multi-location temperature dataloggers was the limited cable length. As a result, the indoor temperature sensor may have been too close to the stove, and the outdoor temperature sensor may have been too close to stove exhaust outlets, influencing the data. The positioning of the temperature sensor on the stove surface was also inconsistent between different households, since the primary consideration was to keep the sensor out of the families' way. In the future, more effort can be made to keep the stove surface temperature sensor in a consistent location relative to the position of the flame.

Going forward, the indoor temperature's heating and cooling responses can be used to develop overall thermal models of households. However, more measurements are needed on the thermal responses of large clay stoves and other significant thermal masses within households, as well as house dimensions, air infiltration rates, chimney exhaust flow rates, and the thermal conductivity of the walls and roof. More analysis of the humidity measurements can also be performed, as humidity is a factor in determining household thermal comfort.

More water boiling tests should conducted on future field visits. In January 2022, only one test was performed on an improved clay stove with a chimney, and more WBTs should be performed on this style of stove, so that results can be compared to traditional clay stoves. WBTs should also be performed on traditional clay stoves in Chakrata, which provided the basis for the model stove in D-Lab, in order to directly compare the performance of the same stove design in the field and in the lab. The WBT sensor system for field tests could also incorporate an additional anemometer to measure the airflow velocity into the stove or the airflow velocity of chimney exhaust.

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Chapter 5

A Novel Methodology for Household Energy Evaluation

Many testing methodologies and standards have been developed for traditional biomass cookstoves, which generally focus on the stoves' efficiency, emissions, safety, and durability. However, the most commonly used testing protocols do not account for stoves used for both cooking and space heating, and there are no common methodologies for holistically evaluating energy outcomes for households that use biomass stoves.

This chapter proposes a methodology for evaluating the generation and flow of energy in rural households with biomass stoves, expanding on existing protocols that focus solely on cookstove performance. The methodology assesses stove performance for both cooking and space heating, pollution levels, house ventilation, and the heating and cooling response of the home. These interconnected elements can complicate the implementation of improved stove designs, as a single modification to the household energy system can cause other unexpected or unwanted changes. This methodology aims to gather the data necessary for developing a model of energy flow throughout a house, allowing designers to fully predict the effects of changes in stove design or building architecture.

5.1 Overview of Cookstove Testing Standards

Through the past decades, many testing standards have been developed for biomass-burning cookstoves and heating stoves; these include both national standards for commercial products and stove evaluation metrics from international organizations. A series of common methodologies used to evaluate developing-world biomass cookstoves were developed collaboratively with the global Clean Cooking Alliance (CCA), a public-private partnership organized by the UN to improve cookstove technologies and reduce household air pollution.

The most widely-used of these tests is the Water Boiling Test (WBT), a laboratory testing procedure for biomass cookstoves. The WBT consists of three consecutive phases: the cold-start high-power phase, where the stove starts at room temperature and boils a measured quantity of water, the hot-start high-power phase, where the already heated stove boils a new pot of water, and the simmering phase, where the stove simmers the water just below the boiling point for 45 minutes. Water temperatures, wood use, and emissions levels are monitored throughout the test, and are used to evaluate stove efficiency and other performance metrics [45].

The WBT is effective at comparing the performance of different cookstoves in a controlled setting. However, the test has certain limitations. It is primarily a laboratory test, and the results are frequently not indicative of stove performance in field settings [45]. Local cooks frequently operate the stove differently than researchers, and use the stove for a wide variety of cooking tasks not adequately represented by boiling water. Sometimes, households use firewood with high moisture content or large diameters, or other biomass fuels such as agricultural waste or dung, to fire the stove, differing from the controlled conditions recommended by the WBT procedure.

More field-oriented tests have also been developed to measure the quantity of wood that households use for cooking. The Controlled Cooking Test (CCT) is used to compare the performance of two stoves, usually a traditional cookstove and an improved cookstove. The two stoves are used to carry out the same cooking task, usually the making of a local dish by a local cook, and wood use is measured and compared for both stoves [63]. The Kitchen Performance Test (KPT), also developed by the CCA, is a field test used to quantify household fuel use over a longer period of time. For the KPT, households are provided with a known quantity of fuel, and researchers check back after a period of time to assess the remaining quantity. The KPT allows researchers to determine fuel consumption under typical household conditions, and can be used to compare fuel use with different stoves or in different seasons. However, it is difficult to account for sources of error over the course of the test, and household behavior may change when given a free bundle of wood [51]. While the CCT and KPT offer good field assessments of wood use, they do not assess more complex metrics of cookstove performance, such as thermal efficiency or emissions levels.

In addition to these three tests, the CCA also promotes standards for stove safety and durability. The safety evaluation procedures involve assessing potential hazards associated with cookstove operation, such as dangerously high surface temperatures or the risks presented by fuel and flames [64]. Durability standards assess stoves' responses to various stresses, such as running the stove for an extended period of time, external and internal impacts, material wear and corrosion, and sudden quenching of the stove [65].

In 2018, the International Standards Organization (ISO) developed harmonized laboratory test protocols for open fires and simple cookstoves, drawing from the aforementioned CCA tests and other cookstove testing protocols. These were the first global standards for biomass cookstoves, and in recent years, the ISO protocols have begun to replace the WBT as the most common standard for cookstove testing. The ISO protocols include testing procedures to measure emissions, thermal efficiency, and cookstove power, as well as point-based scoring systems for safety and durability. The protocols also include performance tiers and targets for the above metrics, which are shown in Figure 3-9 [48]. To assess stove performance and pollution levels, water is boiled on the stove at high, medium, and low firepower for 30 minutes each. The stove power levels are determined by manufacturer specifications or field data [66].

The Firepower Sweep Test (FST) evaluates stove performance throughout a gradual decrease and then subsequent increase of firepower, and is similar in principle to the methodology in the ISO protocol. The FST can result in a large range of emissions levels, corresponding to the different levels of firepower. The FST aligns more closely with field data compared to the WBT, which does not offer clear instruction on the operation of the stove and may overestimate the positive effects of improved stoves at reducing emissions [67]. Existing literature has found that the ISO test protocol's results differ from both WBT and FST data. Stove performance under the WBT typically falls within the same performance tier as the ISO test, but the FST yields higher emissions levels that typically place stoves on a worse performance tier [68].

A review of existing standards for biomass-burning stoves shows that while testing procedures for developing-world cookstoves are well-established, there do not seem to be any internationally unified testing procedures for heating stoves. There are many national and regional standards for heating stoves; these standards are generally for commercially sold products, and they are used to regulate stoves' efficiency and emissions of carbon monoxide and particular matter.

These heating stove testing procedures usually begin with burning an ignition batch before testing starts, and assess stove performance at three or four different burn rates. Existing testing protocols generally specify the use of firewood of particular dimensions and species, with the mass of wood burned depending on the size of the stove's combustion chamber. Research has demonstrated differences between the results of controlled-condition tests and real life scenarios, and more realistic heating stove tests are under development [69].

There are also no commonly used standards for evaluating stoves used for both cooking and heating, although many cold-weather areas in developing countries use the same biomass stove for both tasks. The 2018 ISO cookstove testing standards exclude cookstoves which are mainly used for space heating, and the WBT also does not consider the useful energy that stoves generate for space heating.

The lack of consideration for the heating capabilities of improved stoves can affect the success of improved cookstove projects. Rural communities in north India have reported that their use of improved stoves is limited to warmer seasons [20]. There are often tradeoffs in stove design between space heating and cooking, and it is therefore important to assess stoves' performance at both tasks for clean cooking projects in the Himalayan region. The current testing procedures are also limited to evaluating the performance of the stove itself. However, evaluating household energy holistically may provide critical insights into potential avenues of improvement, motivating the new methodology described in this chapter.

5.2 Proposed Methodology for Data Collection

The results of both the laboratory and field tests in Chapters 3 and 4 show the interconnected nature of cooking, space heating, pollution levels, and household ventilation. When the cooking efficiency of a stove is increased, it provides less radiant space heating to the room where the stove is located, and metallic stoves designed in part for space heating are less efficient for cooking. Field tests found that though chimneys reduce household air pollution, they may cause indoor temperatures to cool more rapidly due to the increased air draft through the house; high chimney exhaust temperatures also cause space heating losses. Lab tests found that stronger air drafts can negatively affect certain stove design elements, such as pot stands.

In light of the complexity of household energy systems in colder regions such as the Himalaya, a new methodology is proposed for evaluating holistic household energy performance for developing-world homes that use biomass stoves. This methodology would allow researchers to evaluate stoves' effectiveness with regard to cooking, space heating and pollution, as well as houses' abilities to retain heat. Table 5.1 presents the quantitative parameters that the model will include, as well as the proposed method for gathering the data.

Parameter w/ Units	**Method of Measurement**	**Relevant Area**
Cooking power (W) Stove efficiency (%) Pot power ratio (-) Test duration (min) Test fuel use (kg) Emissions factors (g/MJ) Emissions rates (g/min)	Cookstove performance test	Cooking
Chimney exhaust temperature (°C)	Temperature sensor	Heating
Chimney airflow velocity (m/s)	Anemometer	Heating
Chimney CO and CO_2 levels (ppm) Chimney PM 2.5 and PM 10 ($\mu g/m^3$)	Pollution sensors	Pollution
Rate of daily fuel use (kg/day)	Kitchen Performance Test Surveys	Cooking, heating, pollution
Length of daily stove use (hr)	Stove temperature sensors Surveys	Cooking, heating, pollution
Indoor CO and CO_2 levels (ppm) Indoor PM 2.5 and PM 10 ($\mu g/m^3$)	Pollution sensors	Pollution
Indoor and outdoor air temperature (°C)	Temperature sensors	Heating
Indoor and outdoor humidity (%)	Humidity sensors	Heating
Stove surface temperature (°C)	Temperature sensors	Heating
Room air volume (m^3)	Measuring tape	Heating
Air infiltration rate (m^3/s)	Tracer gas	Heating
Building envelope heat flux (W/m^2)	Thin film heat flux sensor	Heating
Thermal mass heat capacities (J/K)	Measuring tape for dimensions Surveys about materials	Heating
Thermal mass temperatures (°C)	Temperature sensors Infrared thermometer	Heating

Table 5.1: The measurements composing the proposed household energy evaluation methodology, along with suggested methods of data collection.

First, the methodology includes an assessment of cookstove performance through an existing testing protocol, such as the Water Boiling Test, the Firepower Sweep Test. The test can use similar methods for data collection and data analysis as seen in Chapters 3 and 4. The calculations for stove thermal efficiency are restated in Equations 5.1 through 5.3. During the test, the water temperature change within the cooking pots, the weight and types of fuel used, and the test duration should be measured and recorded. With these measurements, the stove's cooking power ($\dot{Q_{cooking}}$), firepower ($\dot{Q_{fire}}$), and cooking thermal efficiency ($\eta_{thermal}$) can be calculated. For cookstoves which accommodate multiple pots, the ratio of the power entering different cooking vessels on the stove should also be characterized. All of a household's stoves should be evaluated in this manner, including LPG stoves and outdoor stoves.

$$\dot{Q_{cooking}} = \frac{\dot{m_{water}} c_{p,water} \sum \Delta T_{pots}}{\Delta t} \tag{5.1}$$

$$\dot{Q_{fire}} = \frac{\Delta m_{fuel} HV_{fuel}}{\Delta t} \tag{5.2}$$

$$\eta_{thermal} = \frac{\dot{Q_{cooking}}}{\dot{Q_{fire}}} \tag{5.3}$$

Beyond the cooking performance parameters evaluated in existing testing protocols, additional calculations are needed to find the space heating power ($\dot{Q_{heating}}$) provided by the stove. For unvented stoves, it can be assumed that all energy not used for cooking contributes to the heating of the room, either through radiation or advection of hot emissions gases. For stoves with chimneys or kitchens with ventilation features such as a hole in the ceiling or chimney hood, the energy lost through hot exhaust gases exiting the house should be considered. The space heating power provided by the cookstove is expressed in Equation 5.4.

$$\dot{Q_{heating}} = \dot{Q_{fire}} - \dot{Q_{cooking}} - \dot{Q_{exhaust}} \tag{5.4}$$

The rate of energy loss through the chimney ($\dot{Q_{exhaust}}$) can be calculated from the temperature and airflow rate at the exit of the chimney, as seen in Equation 5.5. These parameters can be measured by placing a temperature sensor and an anemometer in the path of the chimney's outlet. The chimney exhaust flow is unlikely to be constant in speed or temperature, so these parameters should be measured continuously and averaged over a period of time. In addition, chimney temperature, airflow, and pollution sensors should be selected for their durability, as they may be damaged by the high temperature, humidity, and particulate levels.

$$\dot{Q}_{exhaust} = \rho_{air} v_{avg} A_{chimney} c_{p,air} (T_{exhaust} - T_{outside}) \tag{5.5}$$

The anemometer should be placed in the center of the chimney pipe, and the airflow speed profile across the chimney should be considered, as the airflow speed will be slower near the walls of the chimney. The Reynolds number (Re), which can be calculated from Equation 5.6 using the chimney diameter and fluid velocity, density, and viscosity, informs this airflow profile. For a chimney pipe with a circular cross-section, the bulk velocity in turbulent flow can be approximated as the center velocity; for laminar flow, the bulk velocity can be approximated as half the center velocity [70]. Pipe flow is laminar when the Reynolds number is below 2300, and turbulent when the Reynolds number is above 3500 [70].

$$Re = \frac{\rho v D}{\mu} \tag{5.6}$$

Some of the quantitative parameters required by the methodology can be found through surveying households. These parameters include the daily usage duration for each of the household's stoves and the typical amount of fuel use over time. Fuel use can also be measured with a Kitchen Performance Test, which may offer more accurate results compared to a survey. While this methodology focuses on the use of biomass stoves, it may be informative to also track the fuel use rates for improved fuels, such as LPG and electricity. In addition to surveys, stove designs and household layouts should ideally be recorded with sketches and photographs.

The ambient temperature, humidity, and pollution levels within the household should be measured with suitable sensors. These sensors should be paired with a datalogging system, to allow data to be collected at regular intervals over a period of at least a day. The research detailed in the previous chapters have found biomass-burning stoves to emit significant amounts of PM 2.5, PM 10, CO, and CO_2, so these pollution levels should be measured. The methodology also includes the assessment of outdoor levels of temperature and humidity. The stove surface temperature should also be recorded to determine stove use patterns through the day.

More investigation is needed to see how ambient conditions vary throughout a room. For initial validations of the methodology, it may be informative to take these measurements at multiple points within a room, to gauge whether the proximity to the stove changes the temperature, humidity, or pollution levels. It may also be informative to measure ambient conditions in different rooms of the house, not just the kitchen, in order to assess how heat and pollutants travel through the house. For larger buildings such as guest houses, data could be taken from a representative sample of the rooms.

In addition to measuring pollution levels within households, the emissions factors (EF) and emissions rates (ER) of stoves should also be evaluated from cookstove performance test data using Equations 5.7 and 5.8. The emissions factor is the mass of a pollutant released per energy that enters the cooking vessels, and the emissions rate is the mass of a pollutant released per time during the test. Equations 3.7 to 3.13 detail the carbon balance method of calculating the masses of different pollutants emitted. Alternatively, in order to calculate the carbon content of the fuel, a sample of the firewood can be collected and the elemental carbon content measured in a lab.

$$EF = \frac{m_{pollutant}}{Q_{cooking}} \tag{5.7}$$

$$ER = \frac{m_{pollutant}}{t_{test}} \tag{5.8}$$

For houses with chimneys, not all of the pollutants released by the stove enter the house, as some pollutants are removed as chimney exhaust. The mass of pollutants leaving the chimney ($m_{i,exhaust}$) can be calculated from the chimney exhaust airflow rate and the chimney exhaust pollution concentrations, as shown in Equation 5.9. The mass of pollutants entering the household ($m_{i,household}$) as a result of the stove's operation can then be calculated using Equation 5.10.

$$\dot{m_{i,exhaust}} = v_{avg} A_{chimney} C_i \tag{5.9}$$

$$\dot{m_{i,household}} = \sum (\dot{m}_i - \dot{m_{i,exhaust}}) \tag{5.10}$$

In addition to the cookstove's performance metrics and pollution levels, the proposed methodology includes parameters for assessing the way that heat flows through and eventually exits the household. Heat within the household is held in a combination of air and thermal masses. The heat flow rate into or out of both air ($\dot{Q_{air}}$) and thermal reservoirs ($\dot{Q_{thermalmass}}$) can be calculated using their change in temperature over time, as presented in Equations 5.11 and 5.12. These heat flow rates can be used to calculate the heat transfer coefficient between the thermal mass and the air.

$$\dot{Q_{air}} = \rho_{air} V_{room} c_{p,air} \frac{dT_{air}}{dt} \tag{5.11}$$

$$\dot{Q_{thermalmass}} = \sum \rho_{mass} V_{mass} c_{p,mass} \frac{dT_{mass}}{dt} \tag{5.12}$$

Thermal masses can include large clay stoves and other large masses of stone and clay that make up the construction of the house, such as walls or counters. The volumes and materials of any thermal masses should be noted as part of the methodology. Temperature sensors should be placed to measure the surface temperatures of these thermal masses throughout the day. Due to temperature variations within large thermal masses, it may be difficult to determine how the the average temperature of the thermal mass changes over time. For thermal masses of complex geometries, computational heat transfer modeling could help to better understand heat transfer mechanisms such as the diffusion of heat through the material or the transfer of heat from the thermal mass to the air.

To assess the amount of heat contained in the room's air, the room's volume and ambient temperature are needed. House dimensions can be taken with a measuring tape; ideally, researchers should sketch a floor plan of the house, noting the length, width, height, layout, and purpose of each room. Over time, household heat loss results from both infiltration of outside air and the conduction of heat away from the house. The rate of heat loss from conduction of heat through the walls and roof ($\dot{Q}_{conduction}$) can be calculated by assessing the material makeup of the house and the thickness of the construction materials. The thermal resistance of the building envelope can be calculated through those parameters, and a network of thermal resistances can be constructed to model heat loss through conduction using Equation 5.13. The thermal resistance calculations could be paired with and validated by thin film heat flux sensors placed on walls and other outwards-facing surfaces.

$$\dot{Q}_{conduction} = \frac{T_{indoor} - T_{outdoor}}{R_{thermal,walls}} \tag{5.13}$$

There are a variety of potential methods to assess air infiltration rates. The airflow rate to the outside for discrete openings, such as the chimney or an open window, can be assessed through anemometer measurements. Chimney airflow rates should be assessed both during stove operation and when the stove is not being fired. However, much of a household's air infiltration is not through these discrete openings. Air infiltration most prominently occurs near cracks of windows, doors, and gaps between the walls and the roof, and can also occur when construction materials shrink and form small cracks in cold weather [71]. Smoke pencils, or sticks of burning incense in the field, can be used for thermal leak detection; high-speed imaging of moving smoke can also be used to determine the velocity of air through a crack. Air infiltration rates can also change significantly depending on ambient temperatures and wind directions and speeds, and this variation should be kept in mind during data collection.

Rates of overall household air infiltration are most commonly assessed through blower door fan pressurization tests or tracer gas tests [72]. A blower door test assesses the airtightness of a building's envelope by setting up a large fan in a door or other opening into the building and depressurizing the building using the fan. The pressure differential and airflow speed across the fan is then used to calculate the air leakage of the building [73]. Models exist to extrapolate natural air infiltration rates from blower door test results [74], [75]. However, blower door tests require specialized equipment and a reliable electricity source, and would be difficult to implement in rural or remote locations in the Himalaya.

Tracer gas measurements are another method for measuring air infiltration in simple building layouts. It is important that the air within the building is well-mixed, and the method usually has a 5 to 10% error [72]. In a single injection tracer decay test, a known amount of a tracer gas is injected into the house, and the gas concentration is measured again after a span of time. There is also a constant tracer gas injection method, which is better suited to leaky indoor spaces where single injections decay too quickly for reliable measurements. Equation 5.14 provides the air infiltration rate ($\dot{V_{air}}$) for the single injection tracer decay test, and Equation 5.15 provides the air infiltration rate for the constant injection method [76].

$$\dot{V_{air}} = V_{room}\frac{ln(C_{t2}) - ln(C_{t1})}{t_2 - t_1} \tag{5.14}$$

$$\dot{V_{air}} = \frac{\dot{V_{tracer}}}{C_{tracer,avg}} - \frac{V_{room}}{t_2 - t_1}ln(\frac{C_{t2}}{C_{t1}}) \tag{5.15}$$

Both carbon monoxide and carbon dioxide are common tracer gases, raising the possibility of using pollutants released from biomass stoves as a tracer gas. Previous studies have also examined the feasibility of using PM 2.5 as a tracer gas, and found the results to be within the range of accepted error from carbon dioxide tracers [77], [78]. This method has potential and would remove the need to carry an additional tracer chemicals on field visits, but it needs to be further explored and validated. Equation 5.16 shows how the heat loss through air infiltration ($\dot{Q_{infiltration}}$) can be found once the air infiltration rate is known. The air infiltration rate can also be used to calculate the rates of pollutant removal from the household.

$$\dot{Q_{infiltration}} = \dot{V_{air}}\rho_{air}c_{p,air}(T_{indoor} - T_{outdoor}) \tag{5.16}$$

5.3 Proposed Household Energy Model

The information provided by the data collection methods in Section 5.2 can be used to analyze the magnitude and time scale of the flow of energy and pollutants within a household over the course of a day. The overall movement of energy within the house can be summarized in Equations 5.17 and 5.18.

During cooking, the heat generated by the stove enters either the cooking vessel, the air of the household, the stove, or is lost to the outside as exhaust for chimneyed stoves.

$$\dot{Q}_{fire} = \dot{Q}_{cooking} + \dot{Q}_{air} + \dot{Q}_{thermalmass} + \dot{Q}_{exhaust} \tag{5.17}$$

Once the stove has stopped introducing energy into the household, the heat redistributes itself between the air and thermal masses and eventually exits the house through conduction or exfiltration.

$$\dot{Q}_{air} = \dot{Q}_{thermalmass} - \dot{Q}_{conduction} - \dot{Q}_{infiltration} \tag{5.18}$$

Through observing the operation of the cookstove, the temperature changes in air and thermal masses, and changing pollution levels in the home, the flow of energy through the house over the course of a typical day can be modeled. This model could take the form of a Microsoft Excel spreadsheet or code in MATLAB or Python. Establishing a thorough understanding of energy flow allows researchers to evaluate the effect of changes made to the household energy system. This model would be of great help in the design and implementation of clean cooking and heating solutions by predicting quantitative heating, cooking, and pollution outcomes.

For example, the proposed introduction of a chimney into a household is known to reduce pollution levels. However, the chimney's exhaust also removes heat from the house which could be otherwise used for space heating, and the chimney may also increase the air draft through the house when the stove is not being operated. This proposed model would allow researchers to quantify the changes to stove space heating power and the indoor temperature of the household over the course of the day, which a cookstove performance test would not capture. The model can be used as a tool for co-design in conjunction with local communities. The predicted outcomes resulting from changes to the household energy system can be presented to households, and they can provide feedback on whether these changes would be acceptable. The model would help prevent unexpected or unwanted changes to household energy as a result of the introduction of improved cookstoves.

In addition to the data collected by the methodologies in Section 5.2, the model requires information about quantitative stove performance changes resulting from new cookstove designs. These changes could be evaluated through conducting experiments with current cookstove testing protocols, or through computational models of cookstove combustion and heat transfer. The performance of the new solutions can then be incorporated into the overarching household energy model. Stove-specific parameters that should be considered include cooking efficiency, pot power ratio, fuel use, cooking duration, heating efficiency, thermal mass, pollutant levels, emissions rates, and emissions factors. Changes to the household energy system when the stove is not being fired should also be considered; for example, the installation of a chimney could increase the passive air infiltration rate of the house.

The methodology should be paired with surveys and discussions about communities' desired household energy outcomes, which may differ between regions. For example, some houses may prefer a stove with lower thermal mass, such as the metallic stoves in Kyanjin Gompa that warm up the kitchen quickly and effectively on cold mornings, but also cool rapidly overnight. However, if a household sleeps in a room adjacent to the stove and wishes to stay warm throughout the night, as is done in Chakrata, a stove with a larger thermal mass may be preferred. The model will be able to predict household temperature and energy flow patterns, but local feedback will determine if those patterns are acceptable.

The proposed methodology does not currently address non-technical and qualitative stove design requirements. These parameters play important roles in the adoption of improved cookstoves and include the cost of improved stoves and fuels, the ease of stove maintenance and stove operation, and the taste of food. Households should also be surveyed regarding changes to these variables, and they should be kept in mind throughout the stove design process.

Another limitation of the unified household energy model is the extensive amount of data needed. The methodology requires many measurements from each individual household, so it may prove difficult to perform the assessment on multiple households in a short amount of time. Ideally, data could be collected in multiple households over multiple days, and a sample of household energy data could be obtained for the different seasons of the year. The methodology could be made less time-consuming by simplifying some steps, such as shortening the cookstove performance test to only one phase or reducing the amount of water boiled for the cookstove performance test. As more data are gathered, it may also be possible to identify patterns that allow researchers to create the household energy model with less information.

The current model is better suited to households with attached kitchens, where the heat from the kitchen can spread throughout the house. In the future, the model can be extended to more complex household layouts, such as households with an exterior kitchen where hot coals are carried into the main house for space heating. The model could also be expanded to include assessments of the potential of alternate energy sources, such as measuring the solar insolation reaching the area.

Going forward, more data need to be collected in the field to validate the methodology, and the household energy model should be developed for a few households. The model can be developed concurrently with and assist in the design of improved cooking solutions.

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Chapter 6

Conclusion

6.1 Summary of Results

Biomass stoves are used for cooking and space heating in developing countries throughout the world. The smoke released by these stoves causes pulmonary and cardiac diseases, which lead to millions of premature deaths each year [2]. There has been extensive work in the past decades to develop improved cookstove designs. However, economic barriers, supply chain issues, and cultural incompatibilities can hinder the implementation of these new technologies. One of MIT D-Lab's research projects focuses on improving the performance of biomass stoves and reducing household air pollution in the Himalayan region. The Himalaya presents unique challenges for the dissemination to improved cookstoves, due to the remoteness of the region and the high space heating needs met by biomass fuels.

A two-pot handmade clay stove based on stoves found in north India was constructed in D-Lab to characterize the performance metrics of traditional Himalayan stoves. The stove's performance was evaluated in D-Lab's Burn Lab with Water Boiling Tests; pollutant levels, temperatures within the stove environment, and fuel use were tracked throughout the tests. The default fuel for stove operation was kiln-dried hardwood, and tests were also conducted with air-dried hardwood for comparison. Two simple modifications to the stove, a grate and pot stands, were also tested and compared to the stove performance at the standard condition.

For all lab conditions, the model clay stove's thermal efficiency measured between 13 and 16%, and between 400 and 500 W of power entered the pot. The air-dried wood and the addition of the grate did not significantly change any of the stove's performance metrics. The addition of pot stands led to more energy entering the primary pot and less entering the secondary pot, due to the gap created between the stove and the pots. However, the pot stands did not change the stove's overall efficiency. One test performed with the Burn Lab's fume hood face barrier lowered suggested that pot stands were less effective with strong air drafts entering the stove. As a result, pot stands may not be compatible with chimneys, another common stove improvement that can increase airflow through the stove.

Under standard test conditions in lab, average CO2 levels measured nearly 1000 ppm above ambient levels. Average CO levels measured 24 ppm, and average PM 2.5 levels measured at 53 mg/m^3. The CO and PM emissions factors and thermal efficiency all rank low on the ISO 2018 stove performance standards, at either Tier 0 or 1. Pollution levels were generally highest in the middle of the tests, when the fire was burning strong, but there were also sharp increases in pollutant levels when the fire was extinguished. Stove interior temperatures were higher in the front of the stove, and there were large differences between stove surface temperatures and stove interior temperatures due to clay's high thermal mass. The stove performed better during the hot start phase of the WBTs compared to the cold start phase, with higher efficiencies and decreased test durations. Improving the stove's performance upon ignition is a potential avenue to increasing cooking efficiency.

The D-Lab team conducted a field visit to north India and Nepal in January 2022, where communities were surveyed and data were gathered on household ambient conditions and cookstove performance in the field. The team visited villages with a variety of climates and elevations to gain a better understanding of the different household energy needs present throughout the Himalayan region. Overall, households primarily used biomass fuels to cook. Firewood was the most common fuel, with yak dung also used in conjunction with firewood at higher altitudes. Biomass fuels could generally be gathered for free or at low cost; many households also had

LPG stoves, which were used less often. Clay stoves were used at lower elevations, while metallic stoves were common at elevations above 3500 meters in Nepal due to their effectiveness at space heating. Stove designs varied between different villages and also between households within a village; household size, layout, and construction materials were also highly varied. While there are broad similarities in stoves and fuels among Himalayan communities, individual households have different preferences and different energy needs, and no one solution will be suitable for all households.

Stove maintenance was found to be an issue in Kyanjin Gompa, a high-altitude village in Nepal where most households used manufactured metallic stoves. The stoves were not designed for ease of maintenance, and chimneys were clogged or leaking, leading to more smoke entering into the house. Households in Kyanjin Gompa also modified their stoves to better suit their needs, but these modifications could negatively affect the stove's performance. For example, some households partitioned the firebox to channel more heat to the primary pot, which could also block airflow to the chimney. As the D-Lab team moves forward into designing stove solutions, it is important to consider stove maintenance and make sure designs fit the needs of the user.

Analysis of indoor ambient conditions showed that all households' average temperatures fell below the World Health Organization's recommendation of 18°C. Both indoor temperatures and indoor pollution levels increase when the cookstove is fired; stove operation patterns were assessed by measuring stove surface temperature. When the stove was fired, the kitchen temperature in all households increased by a rate of 0.1 to 0.4°C/min. The indoor temperature cooled exponentially overnight for all households, and the exponential time constant varied between 2 and 6 hours. Households with chimneys generally had smaller exponential time constants, suggesting that chimneys lead to higher drafts that cool rooms faster. Indoor PM levels and CO levels were far above WHO standards. The presence of a chimney was found to roughly halve pollution levels compared with households without chimneys, but pollution in chimneyed kitchens still remained at unacceptable levels.

For the Chakrata region in north India, ambient household data were collected for three months, from October to December 2021. Analysis found that as temperatures decreased as the season changed from fall to winter, the average pollution levels in the households increased significantly. As pollution levels are partially driven by space heating needs, solutions to reduce household air pollution from biomass stoves in the Himalaya and other cold regions should focus on improving both cooking and heating systems.

Stoves in the field were found to be less efficient than the model stove tested in lab. Field WBTs of stoves yielded cooking efficiencies of between 4 and 13%. This disparity may be partly due to field tests using firewood with higher moisture content and less effective ignition materials. Metallic stoves were less efficient at cooking than clay stoves, since they were designed to also radiate heat to the environment. A grate tested in the field also did not improve stove performance, matching lab test results. Across all the different stoves tested in the field, thermal efficiency was found to be negatively correlated with both fuel use and test duration.

The results obtained in the field study show that it is important to consider the connections between cooking, heating, and air pollution in the rural Himalaya. However, many existing testing protocols for biomass cookstoves only focus on the cooking performance of the stove. A new methodology for data collection is proposed for evaluating the overall energy flow, including space heating, in households which primarily use biomass stoves. Information gathered through the methodology can be used to create models of household energy responses, and these models can be subsequently used to predict how improved cookstove technologies will change cooking, heating, and pollution outcomes.

6.2 Next Steps

Using the data gathered from the Burn Lab tests and the 2022 field visit, the D-Lab team is moving towards the design phase of the project. Going forward, the team will design and prototype improved cookstoves with higher efficiencies and reduced household air pollution levels. The collected data on stove performance metrics and household ambient conditions will provide baselines for determining design requirements. In addition, surveys and observations from the field visit will inform qualitative requirements for stove design, such as the ease of maintenance. The team has decided to focus on improvements to biomass-burning stoves instead of introducing alternative fuels, due to the importance of keeping fuel costs low and the difficulty of supply chains in the Himalaya, especially in rainy or snowy seasons.

The addition of a chimney to traditional stoves is a promising solution, as chimneys were shown to significantly decrease pollutant concentrations in households. However, chimneys may affect stoves' space heating capabilities, as some heat will be lost as exhaust, and analyses of overnight cooling patterns suggest that kitchens with chimneys cool down faster due to the induced draft. Going forward, a chimney should be installed in the D-Lab model stove, and test results should be compared with the chimneyless stove to determine the impact on stove performance. The team will also explore ways to further reduce household air pollution levels after a chimney is added, as chimneys still leave a significant amount of pollutants inside the kitchen. More work can also be done on the design of water heaters coupled to chimneys, which were present in some households in Nepal, but were generally non-functional and disused.

Further investigation can also be performed into improving the current grate and pot stand prototypes, as well as exploring other minor modifications that do not require significant and permanent changes to the stove. Grates with a square form factor placed at the mouth of traditional clay stoves were found to be ineffective, but a long thin grate inserted into enclosed stoves may be an improvement. Pot stands were commonly found in the field and were successful in channeling more energy into a single pot in lab tests; further optimization should be done on the height of the pot stands. There is also the possibility of building and testing other common Himalayan stove designs in the Burn Lab.

In addition to more testing in D-Lab, the team is also planning another field visit to India and Nepal in the summer of 2022. During this visit, the team plans to test solution prototypes in the field and receive feedback from rural communities. The team will also work closely with stove manufacturers in order to evaluate the economic feasibility and ease of manufacturing of D-Lab's proposed solutions, as well as help the manufacturers improve their stove designs.

In the field, the team will also test and improve the proposed household energy evaluation methodology. Enough data should be collected using the methodology to create an energy flow model for a handful of households. The team can then use the model to predict how new stove designs will change cooking and heating outcomes, and seek feedback from local communities on whether the proposed changes are acceptable. In order to develop effective solutions to reduce household air pollution and improve the health of biomass stove users, we must consider the household energy system as a whole and bring together the technical and human aspects of the problem at hand.

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Appendices

Appendix A: Sensors Used

Purpose, or Parameter Measured	**Quantity**	**Manufacturer**	**Model**
Stove interior temperatures	4	Omega	TJ36-CAIN-18U-6
Fire temperature	1	Omega	TJ36-CAIN-316U-12
Water and stove surface temperatures	3	Maxim Integrated	DS18B20
CO2	1	Alphasense	IRC-A1
CO	1	Alphasense	CO-AF
NO2	1	Alphasense	NO2-A1
NO	1	Alphasense	NO-A1
O2	1	Alphasense	O2-A2
SO2	1	Alphasense	SO2-AF
PM 2.5	1	TSI	DustTrak II 8530
Load cell amplifier	1	AVIA Semiconductor	HX711
Pump for exhaust isolation	1	IMPACT Instrumentation	317M
Microcontroller	1	Arduino	Arduino Mega
Thermocouple amplifiers	5	Maxim Integrated	MAX31855
Wood moisture meter	1	Extech	MO50

Table A.1: The sensors and equipment used in D-Lab's Burn Lab.

Purpose, or Parameter Measured	**Quantity**	**Manufacturer**	**Model**
Ambient datalogger indoor/outdoor temperature and humidity	2	Adafruit	DHT22
Ambient datalogger stove surface temperature	1	Maxim Integrated	DS18B20
Ambient datalogger microcontroller	1	Arduino	Arduino Pro Mini
Sensen temperature and humidity	1	Bosch Sensortec	BME280
Sensen CO	1	SPEC Sensors	3SP-CO-1000F
Sensen CO2	1	Figaro USA	CDM7160
Sensen PM 2.5 and PM 10	1	Plantower	PMSA003I
Stove test fire and other high temperatures	2	Omega Model	TJ36-CAIN-18U-6
Stove test water and other low temperatures	5	Maxim Integrated	DS18B20
Stove test exhaust temperature datalogger	1	Lascar Electronics	EL-USB-TC-LCD
Wood and water weights	1	Acculab	VIC-3101
Stove test microcontroller	1	Arduino	Arduino Uno
Stove test thermocouple amplifiers	2	Maxim Integrated	MAX31855
Wood moisture meter	1	Extech	MO50

Table A.2: The sensors and equipment used during the January 2022 field visits to India and Nepal.

Appendix B: Fuel Heating Values

Table B.1 lists the firewood species used in both the lab and the field and their energy contents [79]–[81]. The mixed hardwood used as the primary fuel in the Burn Lab tests was assumed to be oak, a common hardwood used for firewood. In the field, multiple species of wood were sometimes used within the same test; in those cases, what seemed to be the predominant type of wood was used for the analysis. Previous literature on the heating value of yak dung was difficult to find. Dried cattle dung has been found to be a heating value of between 11 and 19 MJ/kg [82], [83], so the heating value of yak dung was assumed to be in the middle of that range.

Fuel Type	**Heating Value**	**Fuel Use Location**
Oak	16.2	Burn Lab
Birch	16.2	Burn Lab
Cedar	14.7	Burn Lab
Chir pine	17.8	Agoda, Langtang Valley, Salambu (improved stove)
Rhododendron wood	19.0	Kyanjin Gompa, Salambu (traditional stove)
Sal wood	18.0	Dehradun
Yak dung	15.0	Kyanjin Gompa

Table B.1: The heating values of the fuels used in water boiling tests in both the Burn Lab and the field.

Appendix C: Lab Test Full Results

Test Date	Test Conditions	Avg Fire Temp (°C)	Avg Front Gap Temp (°C)	Avg Back Gap Temp (°C)	Avg Front Wall Temp (°C)	Avg Back Wall Temp (°C)	Avg Surface Temp (°C)
10/12/2021	Kiln-dried hardwood, no stove modifications (initial run)	413	195	36	-	59	-
10/14/2021	Kiln-dried hardwood, no stove modifications (initial run)	412	216	141	283	66	-
11/17/2021	Kiln-dried hardwood, no stove modifications	564	238	75	156	53	-
11/20/2021	Kiln-dried hardwood, no stove modifications	514	370	117	107	44	-
11/21/2021	Kiln-dried hardwood, no stove modifications	530	245	108	177	114	-
11/23/2021	Kiln-dried hardwood, no stove modifications	552	268	123	230	47	-
11/27/2021	Cedar wood, no stove modifications	539	305	109	183	37	-
2/23/2022	Cedar wood, no stove modifications (fume hood barrier lowered)	535	338	165	211	106	32
11/30/2021	Birch wood, no stove modifications	458	364	91	175	-	-
2/26/2022	Birch wood, no stove modifications (fume hood barrier lowered)	578	372	209	235	144	61
12/2/2021	Kiln-dried hardwood, pot stands (prototype)	525	518	78	167	-	-
3/3/2022	Kiln-dried hardwood, pot stands (fume hood barrier lowered)	461	284	75	209	56	39
3/7/2022	Kiln-dried hardwood, pot stands	245	383	23	164	-	49
3/15/2022	Kiln-dried hardwood, pot stands	391	379	27	187	26	39
3/26/2022	Kiln-dried hardwood, pot stands	465	469	25	214	-	-
12/5/2021	Kiln-dried hardwood, grate (prototype)	567	379	89	173	29	-
3/1/2022	Kiln-dried hardwood, grate (fume hood barrier lowered)	525	410	158	277	85	51
3/10/2022	Kiln-dried hardwood, grate	545	353	151	247	53	33
3/17/2022	Kiln-dried hardwood, grate	548	471	118	238	42	41
3/22/2022	Kiln-dried hardwood, grate	512	423	193	311	107	42
3/24/2022	Kiln-dried hardwood, grate	511	401	185	266	130	-

Table C.1: Stove temperatures for each individual test performed with the model clay stove in the Burn Lab. The tests used in the average results for each condition are highlighted in light gray.

Test Date	Test Conditions	Max CO2 (ppm)	Avg CO2 (ppm)	Max CO (ppm)	Avg CO (ppm)	Max PM2.5 (mg/m^3)	Avg PM2.5 (mg/m^3)	CO EF (g/MJ)	CO ER (g/min)	CO2 EF (g/MJ)	CO2 ER (g/min)	PM EF (g/MJ)	PM ER (g/min)
10/12/2021	Kiln-dried hardwood, no stove modifications (initial run)	-	-	-	-	-	-	-	-	-	-	-	-
10/14/2021	Kiln-dried hardwood, no stove modifications (initial run)	-	-	-	-	-	-	-	-	-	-	-	-
11/17/2021	Kiln-dried hardwood, no stove modifications	2151	1388	89	31	291	53	17.4	0.471	744	20.2	25.9	0.701
11/20/2021	Kiln-dried hardwood, no stove modifications	-	-	31	13	49	11	-	-	-	-	-	-
11/21/2021	Kiln-dried hardwood, no stove modifications	2342	1471	58	24	292	56	11.7	0.319	699	19.1	23.5	0.642
11/23/2021	Kiln-dried hardwood, no stove modifications	2129	1567	60	29	394	93	12.6	0.371	708	20.8	35.8	1.06
11/27/2021	Cedar wood, no stove modifications	-	-	29	11	142	14	-	-	-	-	-	-
2/23/2022	Cedar wood, no stove modifications (fume hood barrier lowered)	1733	1157	-	-	232	15	-	-	-	-	-	-
11/30/2021	Birch wood, no stove modifications	2303	1535	39	16	171	40	6.60	0.183	660	18.3	14.6	0.406
2/26/2022	Birch wood, no stove modifications (fume hood barrier lowered)	1601	1227	-	-	65	15	-	-	-	-	-	-
12/2/2021	Kiln-dried hardwood, pot stands (prototype)	2691	1878	28	13	109	13	2.96	0.108	464	16.9	2.45	0.0892
3/3/2022	Kiln-dried hardwood, pot stands (fume hood barrier lowered)	2613	1711	-	-	-	-	-	-	-	-	-	-
3/7/2022	Kiln-dried hardwood, pot stands	1924	1284	-	-	66	7	-	-	-	-	-	-
3/15/2022	Kiln-dried hardwood, pot stands	2130	1343	-	-	95	9	-	-	-	-	-	-
3/26/2022	Kiln-dried hardwood, pot stands	1964	1232	-	-	59	7	-	-	-	-	-	-
12/5/2021	Kiln-dried hardwood, grate (prototype)	2215	1551	83	23	254	37	11.7	0.254	814	17.7	16.4	0.356
3/1/2022	Kiln-dried hardwood, grate (fume hood barrier lowered)	1400	1044	-	-	74	14	-	-	-	-	-	-
3/10/2022	Kiln-dried hardwood, grate	1917	1302	-	-	248	33	-	-	-	-	-	-
3/17/2022	Kiln-dried hardwood, grate	2032	1256	-	-	101	20	-	-	-	-	-	-
3/22/2022	Kiln-dried hardwood, grate	1900	1183	-	-	-	-	-	-	-	-	-	-
3/24/2022	Kiln-dried hardwood, grate	1435	931	-	-	373	61	-	-	-	-	-	-

Table C.2: Average and maximum pollution levels, emissions factors, and emissions rates for each individual test performed with the model clay stove in the Burn Lab. The tests used in the average results for each condition are highlighted in light gray.

Test Date	Test Conditions	Wood Burned (kg)	CS Duration (min)	HS Duration (min)	Total Duration (min)	CS Power Into Pots (W)	HS Power Into Pots (W)	Avg Power Into Pots (W)	CS Pot Power Ratio (-)	HS Pot Power Ratio (-)	Avg Pot Power Ratio (-)	Avg Firepower (W)	CS Efficiency (%)	HS Efficiency (%)	Avg Efficiency (%)
10/12/2021	Kiln-dried hardwood, no stove modifications (initial run)	0.817	32.4	16.3	48.6	341	628	437	4.25	4.48	4.32	4368	7.81	14.37	10.00
10/14/2021	Kiln-dried hardwood, no stove modifications (initial run)	0.900	36.5	20.1	56.6	352	511	408	2.80	3.30	2.98	4106	8.58	12.44	9.95
11/17/2021	Kiln-dried hardwood, no stove modifications	0.836	30.0	19.1	49.1	388	552	452	3.03	3.13	3.07	3805	10.19	14.50	11.87
11/20/2021	Kiln-dried hardwood, no stove modifications	0.669	23.4	19.8	43.2	432	617	517	11.10	2.73	7.26	3231	13.37	19.08	15.99
11/21/2021	Kiln-dried hardwood, no stove modifications	0.919	31.9	21.1	53.1	414	250	456	2.37	3.08	2.65	3564	11.60	14.59	12.79
11/23/2021	Kiln-dried hardwood, no stove modifications	0.865	30.0	16.6	46.6	434	593	491	2.46	4.85	3.31	4062	10.67	14.61	12.08
11/27/2021	Cedar wood, no stove modifications	0.865	32.1	28.2	60.2	351	401	374	4.75	3.22	4.03	3351	10.47	11.96	11.17
2/23/2022	Cedar wood, no stove modifications (fume hood barrier lowered)	0.659	44.3	23.3	67.6	339	584	424	2.14	2.26	2.18	2255	15.04	25.92	18.79
11/30/2021	Birch wood, no stove modifications	0.786	30.2	17.4	47.5	463	382	603	4.57	4.24	4.45	3285	11.64	18.37	14.10
2/26/2022	Birch wood, no stove modifications (fume hood barrier lowered)	0.897	38.6	25.3	63.9	394	602	476	1.60	1.32	1.49	3501	11.24	17.19	13.60
12/2/2021	Kiln-dried hardwood, pot stands (prototype)	0.429	18.5	15.8	34.4	580	639	607	5.61	22.68	13.48	2873	20.20	22.23	21.14
3/3/2022	Kiln-dried hardwood, pot stands (fume hood barrier lowered)	0.910	34.1	24.5	58.6	371	495	423	2.74	2.08	2.46	3865	9.59	12.81	10.93
3/7/2022	Kiln-dried hardwood, pot stands	0.473	31.0	21.2	52.2	330	409	362	8.58	25.29	15.37	2338	14.12	17.49	15.49
3/15/2022	Kiln-dried hardwood, pot stands	0.439	29.2	22.5	51.6	373	346	409	17.14	38.02	26.22	2248	15.40	18.18	16.61
3/26/2022	Kiln-dried hardwood, pot stands	0.548	20.5	17.4	37.9	463	627	538	30.30	5.18	18.77	3480	13.24	17.91	15.38
12/5/2021	Kiln-dried hardwood, grate (prototype)	0.850	41.3	19.5	60.8	261	577	362	6.10	3.80	5.36	3172	8.21	18.20	11.42
3/1/2022	Kiln-dried hardwood, grate (fume hood barrier lowered)	0.680	35.9	23.3	59.2	361	528	427	2.76	2.23	2.55	2664	13.57	19.83	16.04
3/10/2022	Kiln-dried hardwood, grate	0.603	29.0	18.6	47.6	437	604	503	2.66	2.72	2.68	3103	24.9	21.8	23.4
3/17/2022	Kiln-dried hardwood, grate	0.667	33.6	19.6	53.2	350	565	430	3.82	2.82	3.45	3026	11.58	18.68	14.20
3/22/2022	Kiln-dried hardwood, grate	0.630	42.6	25.8	68.4	356	597	447	1.93	1.56	1.79	2301	15.48	25.94	19.42
3/24/2022	Kiln-dried hardwood, grate	0.896	39.3	29.7	69.0	377	441	404	1.72	1.92	1.81	3362	11.21	13.11	12.03

Table C.3: Stove performance metrics for each individual test performed with the model clay stove in the Burn Lab, including separate cold start and hot start statistics. The tests used in the average results for each condition are highlighted in light gray.

Appendix D: Field Visit Survey Questions

A. Identification and Basic Demographics

1. Interview date and time:
2. Interviewer name:
3. State:
4. Local Government Area:
5. Community/village:
6. Other location information:
7. GPS coordinates (from phone if possible):
8. Altitude (from phone if possible):
9. Respondent name:
10. Respondent gender:
11. Respondent age:
12. Number of people in household:

B. Fuel Use Questions

1. What energy sources do you use for the following activities?

Energy Source	Cooking	Heating water	Space Heating	Lighting
Electricity (ask about source)				
Kerosene				
LPG/gas				
Wood				
Dung				
Solar				
Other				

2. For the energy sources used above, please answer the following questions.

Energy Source	What is the cost?	How much fuel is used daily?	How do you collect the energy source/fuel?
Electricity (ask about source)			
Kerosene			
LPG/gas			
Wood			
Dung			
Solar			
Other			

3. Does the amount of fuel used vary throughout the year? If so, during which months do you use the most fuel for cooking and heating?
4. Collection of Firewood
   (a) How frequently do you collect wood or other biomass fuels?
   (b) How many hours does one trip for wood collection take?
   (c) What species is the firewood?
   (d) Note the shape, dimensions, and weight of wood. How consistent are these parameters?
   (e) Take measurements of the firewood's moisture levels at a few different locations along the length of the wood.

C. Cooking Practices

1. What type(s) of cookstoves does your family use? Describe the stoves here, and sketch the stoves and their dimensions.
2. Stove Construction
   (a) How often do you buy or build a new stove?
   (b) What are common causes of buying or building a new stove?
   (c) Who in the household buys or builds new stoves?
   (d) If the stove is built, what materials is it made from? Provide an overview of the construction procedure.

   (e) How much money does it take to buy or build a new stove?

3. Stove Operation
   (a) During the day, at what times do you use your cooking appliances?
   (b) How many hours per day is each stove used for cooking?
   (c) How long does it take to prepare the stoves for cooking?
   (d) If there are multiple stoves, what foods/drinks do you prepare using each stove?
4. Cooking procedures
   (a) Describe the size, shape, and material of cooking pots used. Do the pots have lids?
   (b) What utensils are used for cooking?
   (c) How is the fire ignited?
   (d) How is the fire tended throughout the cooking process? Where is the fire located in the stove?
5. What do you like about your current cooking appliances?
6. What would you improve about your current cooking appliances?
7. If multiple stoves are used, what are the strengths and weaknesses of each one?

D. Household Heating

1. What appliances does your household use for space heating?
2. During what hours do you heat your house each day?
3. How many hours per day is each appliance used for heating?
4. During what months in the year does your home require the most heating?
5. Is your home warm and comfortable throughout the year?
6. What do you like about your home heating system?
7. What would you improve about your home heating system?
8. Do you experience smoke or other air pollution when cooking and heating in your home? If yes, are there any months during the year when pollution is worse?

E. House Construction and Layout

1. Basic Questions

   (a) How many floors/levels are there in the home?
   (b) Which rooms are located on each level?
      i. Ground level:
      ii. Level 1:
      iii. Level 2:
2. Sketch a top-down floor plan of the house, including 1) dimensions, 2) the locations of rooms, doors, windows, stove, heater, and additional openings such as chimneys or open spaces in the roof, and 3) the cardinal direction (north/south/east/west) with respect to the house
3. Sketch a front or side view of the house that shows the heights of the wall and roof. Note the wall in the top-down floor plan that corresponds to this sketch.
4. Sketch a cross section of the wall, including the different materials and their thicknesses. Indicate where the outside/inside of the house is on the sketch.
5. What material is the flooring? What is the floor thickness?
6. What material is the roof? What is the roof thickness?
7. What are the dimensions of the door(s) in the house?
8. What are the dimensions of the windows?
9. Does the house have a chimney or other additional openings to the outside?
   (a) What is the chimney constructed from? How is it made?
   (b) What are the dimensions of the chimney?

F. Wrap-Up

1. Is there anything else you would like to tell us about cooking and heating in your household or in your community?

2. Are you interested in receiving updates and more information about this project and future activities?

   (a) If yes, what type of communication would be best?
   (b) Contact information

3. Any additional observations that may be relevant for understanding household energy?

Appendix E: Field Visit Full Results

Location	**Kitchen 1**			**Living Room 1**			**Kitchen 2**		
Month	**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**	**Oct**	**Nov**	**Dec**
Avg Temperature (°C)	24.4	20.4	19.0	23.3	17.9	15.1	23.3	16.1	13.6
Avg Humidity (%)	56.8	44.2	40.5	60.5	50.9	50.5	63.5	58.9	55.8
Avg CO (ppm)	6	9	11	7	10	11	14	14	13
Max CO (ppm)	165	151	204	42	46	49	39	28	35
Avg CO2 (ppm)	408	452	521	594	568	580	373	371	381
Max CO2 (ppm)	4003	4215	4136	1693	2307	2291	1400	845	1935
Avg PM2.5 ($\mu g/m^3$)	132	175	274	100	141	228	135	155	235
Max PM2.5 ($\mu g/m^3$)	3027	5143	6158	2131	3382	3719	2898	2794	3747
Avg PM10 ($\mu g/m^3$)	179	223	347	142	185	300	170	196	306
Max PM10 ($\mu g/m^3$)	23780	22706	26321	23484	9336	12800	12671	6255	13033
Hours With High PM2.5	12.7	13.0	13.7	11.0	10.5	13.0	11.0	10.5	13.0
Hours With High PM10	5.8	6.2	7.9	6.6	7.6	10.9	6.6	7.6	10.9

Table E.1: Averages of household ambient conditions in Chakrata for the months of October, Novemeber, and December in 2021.

Location	**Stove Type**	**Indoor Temp (°C)**	**Outdoor Temp (°C)**	**Indoor Temp Range (°C)**	**Outdoor Temp Range (°C)**	**In/Out ΔT (°C)**	**Indoor Humidity (%)**	**Outdoor Humidity (%)**	**In/Out ΔH (%)**	**Avg CO (ppm)**	**Max CO (ppm)**	**Avg CO2 (ppm)**	**Max CO2 (ppm)**	**Avg PM2.5** (ug/m^3)	**Max PM2.5** (ug/m^3)	**Avg PM10** (ug/m^3)	**Max PM10** (ug/m^3)
Kyanjin Gompa	Metal ICS	10	0.6	22.2	30.4	9.3	45.9	70.9	-24.9	7	24	-	-	419	5090	549	11638
Kyanjin Gompa	Metal ICS	1.8	-3.1	17.3	14	5	66	77.4	-11.4	7	14	-	-	39	942	83	1942
Kyanjin Gompa	Open Fire	-0.1	-2.5	22	28.8	2.5	94	87	7	5	66	-	-	451	6623	953	27921
Salambu	Clay ICS	13	10.1	20.2	25.7	2.9	87.6	85	-6.4	-	-	-	-	-	-	-	-
Salambu	Clay ICS	16.7	9.6	19.3	8.7	7	80.4	93.9	-13.5	8.8	60	686	1776	1096	6071	1442	9877
Salambu	Clay TCS	11.8	9.5	14.9	18.1	2.3	90.7	99.7	-8.9	6	22	-	-	658	6729	920	18166
Uttarakashi	Clay TCS	14.6	8.1	16.6	16.3	6.5	79.2	-	-	43	345	1488	6374	3056	8480	6871	32561
Agoda	Clay TCS	16.1	6.4	13.2	6	9.6	66	85	-19	37.9	137	1178	3149	2076	7184	3207	21464

Table E.2: Ambient household conditions for each location during the January 2022 field visits.

Location	**Stove Type**	**Avg Fire Temp (°C)**	**Max Fire Temp (°C)**	**Avg Gap Temp (°C)**	**Max Gap Temp (°C)**	**Avg Surface Temp (°C)**	**Max Surface Temp (°C)**	**Avg Exhaust Temp (°C)**	**Max Exhaust Temp (°C)**
Kyanjin Gompa	Metal ICS	459	766	-	-	101	205	-	-
Kyanjin Gompa	Metal ICS	494	694	-	-	128	206	-	-
Langtang Valley	Clay TCS	567	815	576	807	17	18	-	-
Salambu	Clay ICS	652	869	384	730	47	50	246	302
Salambu	Clay ICS	608	776	342	716	29	37	-	-
Agoda	Clay TCS	538	790	435	688	13	17	317	537
Dehradun	Clay TCS	460	700	232	425	22	29	-	-
Dehradun	Clay TCS	304	795	65	365	20	25	-	-

Table E.3: Stove temperatures for the water boiling tests performed in the field.

Location	**Stove Type**	**Avg CO (ppm)**	**Max CO (ppm)**	**Avg CO2 (ppm)**	**Max CO2 (ppm)**	**Avg PM2.5** (ug/m^3)	**Max PM2.5** (ug/m^3)	**Avg PM10** (ug/m^3)	**Max PM10** (ug/m^3)	**CO EF (g/MJ)**	**CO ER (g/min)**	**CO2 EF (g/MJ)**	**CO2 ER (g/min)**	**PM EF (g/MJ)**	**PM ER (g/min)**
Kyanjin Gompa	Metal ICS	4	7	-	-	337	1143	392	1325	-	-	-	-	-	-
Kyanjin Gompa	Metal ICS	6	11	-	-	1260	4420	1855	8065	-	-	-	-	-	-
Langtang Valley	Clay TCS	5	7	-	-	291	1414	383	2528	-	-	-	-	-	-
Salambu	Clay ICS	14	32	875	1038	2799	4885	3561	7195	55.7	3.41	938	57.4	11.42	0.699
Salambu	Clay TCS	6	10	-	-	2673	4187	3574	5864	-	-	-	-	-	-
Agoda	Clay TCS	61	109	1931	3387	6249	7808	13645	22582	49.6	1.94	1482	58.2	5.47	0.215
Dehradun	Clay TCS	35	92	1265	1843	3254	5706	5792	20025	19.0	0.43	651	14.9	1.58	0.036
Dehradun	Clay TCS	13	21	831	1098	3964	6079	6412	14629	22.4	0.71	1168	36.8	6.19	0.195

Table E.4: Average and maximum pollution levels, emissions factors, and emissions rates for the water boiling tests performed in the field.

Location	Stove Type	CS Duration (min)	HS Duration (min)	Total Duration (min)	CS Wood Use (kg)	HS Wood Use (kg)	Total Wood Use (kg)	CS Efficiency (%)	HS Efficiency (%)	Avg Efficiency (%)	CS Pot Power (W)	HS Pot Power (W)	Avg Pot Power (W)	Pot Power Ratio (-)	CS Firepower (W)	HS Firepower (W)	Avg Firepower (W)
Kyanjin Gompa	Metal ICS	72.9	43.6	116.5	0.93	1.11	2.04	4.16	4.5	4.32	223	361	275	-	5369	8033	6366
Kyanjin Gompa	Metal ICS	62.5	34.6	97.1	0.94	0.79	1.73	5.3	6.1	5.66	252	441	319	-	4750	7230	5634
Langtang Valley	Clay TCS	14.9	12.9	27.9	1.35	0.89	2.24	6.04	7.76	6.72	1623	1581	1604	3.58	2688	2037	23861
Salambu	Clay ICS	24.7	15.8	40.5	0.96	0.65	1.61	7.21	10.91	8.7	828	1324	1021	2.43	1148	1214	1174
Salambu	Clay ICS	12.1	11.2	23.3	0.56	0.58	1.14	8.39	7.24	7.81	1241	1189	1216	-	14801	16407	15575
Agoda	Clay TCS	26.0	25.1	51.1	-	-	1.94	5.86	5.73	5.79	661	646	654	-	-	-	11282
Dehradun	Clay TCS	31.2	44.7	75.9	-	-	0.73	16.57	10.93	13.25	476	314	381	-	-	-	2873
Dehradun	Clay TCS	39.6	15.9	55.5	1.11	0.2	1.31	4.59	23.22	7.41	387	868	525	-	8424	3740	7083

Table E.5: Stove performance metrics for the water boiling tests performed in the field.