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Transparent Climate and Health Metrics: An Open Data Dashboard and Wireless Platform for Cookstove Monitoring

Final Report

February 28th, 2017

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1. Executive Summary

This project lays the ground work for sensor-enabled results-based financing for improved cookstoves globally. A tremendous amount of work was accomplished in developing new sensor-integrated wireless platforms, climate and health metrics that can be implemented in a real-time platform for results-based financing, an open data platform, consensus across diverse stakeholders on precise frameworks for monitoring, and a large amount of sensor data from rural households across four states in India.

Every day, 3 billion people rely on burning biomass inside their homes to cook and to provide light and heat. Exposure to the resulting household smoke kills millions and contributes significantly to global climate change. **Improved cookstoves** can save lives and ameliorate climate change, but efforts to get traditional cookstove users to switch often fail. Furthermore, the positive environmental and health impacts that improved cookstoves are supposed to deliver can vary dramatically based on a number of factors, including the stove technology selected, the actual usage of the stove, the fuel consumed, and the context of its use. More information is needed to determine the most appropriate stove technologies, interventions, and accompanying business models required to achieve improved cookstoves' advantages. More information is additionally needed to mitigate business model and investment risks as well as to improve stove designs based on realities on the ground. **Wireless monitoring has the power to make granular data on improved and traditional cookstove use available immediately, enabling timely decision making on the direction of improved cookstove interventions undertaken by governments and global organizations**.

Phase 1 of the Nexleaf-World Bank project was focused on developing an integrated sensor platform, climate and health metrics, and an extensible web-based analytics dashboard. We developed the following: 1) A global monitoring platform to gather near-real-time data on improved and traditional cookstove use and $PM_{2.5}$ remotely for timely analysis and evaluation; 2) An analytics dashboard to view this data by many cookstove stakeholders, ultimately to compare interventions across multiple dimensions (such as demographics, geography, and stove design) based on performance in the field; and 3) Algorithms built into the platform that calculate up-to-the-minute climate, health, and stove adoption metrics, to be used to identify which stove distribution interventions are succeeding and which result in low adoption. In addition, Nexleaf and World Bank convened a one-day workshop with key stakeholders across the sector in Delhi to explore opportunities, barriers, and areas of agreement and disagreement. This group decided to author a joint methodology on “Monitoring for Impact and Behavior Change” for using detailed sensor data for monitoring and financing results pertaining to climate, health, and adoption. The draft methodology has detailed comments from experts incorporated, and will be released upon completion of a larger-scale field trial.

This work was completed through many synergies with the sector facilitated by the World Bank, including sub-contractors Berkeley Air Monitoring Group and The Energy and Resources Institute, and in consultation with Scripps Institution of Oceanography. The partnership with Berkeley Air has been strengthened through this work, with mutually agreed-upon complimentary roles delineated for Nexleaf and Berkeley Air moving forward. Additional beneficial synergies have been forged with the Gold Standard Foundation working group for the already-published black carbon methodology and the soon-to-be-published health credit methodology, as well as the ISO working group.

Overall, the efforts to develop this platform to use sensors to support results-based financing (more specifically called sensor-enabled climate and health financing) for

cookstoves have been met with broad support in the sector. The methodology for sensor-enabled climate financing **was published in *Nature Climate Change*** on October 31st, and was presented at 4 venues in the recently concluded COP22 Climate Summit at Marrakech. **The venues organized by the World Health Organization (WHO), United Nations Environment Programme (UNEP) and the Nordic countries received the Sensor-Enabled Climate Financing (SCF) model with great enthusiasm.** The WHO has requested Nexleaf to give a detailed in-person presentation at the headquarters in Geneva, which is embarking on a major initiative linking climate change with health impacts (Breathe Life).

In addition to field and lab validation of the sensors, there has been tremendous success in the field implementation of the open data platform. Improved and/or traditional stove usage data has been collected from 79 households, and StoveTrace devices are being utilized to understand adoption by World Bank partners Dharma Life, AIREC, SEWA and Envirofit. There are 54 households in two states (Odisha and Tamil Nadu) receiving usage-based payments through the open data platform, using the climate metrics developed under this project.

This work was envisioned in 3 Phases. The current Nexleaf-World Bank project covered Phase 1 of this work, focused on prototyping and field testing an integrated sensor platform, climate and health metrics and an extensible web-based analytics dashboard. This has laid the groundwork for getting to large-scale implementation of remote monitoring for results-based financing. Phase 2 should focus on enhancing the open data platform for scale and privacy-preserving sharing across diverse partners and implementing a field trial of the methodology and platform with Tata Trusts in 500 households. These developments, and the additional work required, are covered in section 5. Phase 3 would entail scaling up the integrated sensor deployment to ten thousand households and increasing the capacity of the open data platform accordingly.

This work aims to enable the most effective and efficient cookstove programs to scale. Initially developed and evaluated for India, it can be applied to improved cookstove programs globally.

2. Milestone Summary

The overall goal of this project was to build a complete platform for remotely monitoring indoor air pollution to enable results-based financing of clean cooking interventions. As evidenced in the specific milestones of the project listed below, this consisted of research, laboratory and field tests to evaluate available $PM_{2.5}$ sensors, meetings with stakeholders to establish appropriate implementation protocols, and technical development of the technology, and creation of a set of health and climate metrics to translate the data in terms of impact. The deliverables of this project have been met with great success, and the following were achieved:

1. Milestone 1: Evaluation and Preparation. To begin, a survey of commercially available, affordable, and technically compatible $PM_{2.5}$ sensors had to be conducted. Nine $PM_{2.5}$ sensors were evaluated, and three of them (PATS+, HAPEx Nano, and AirBeam) were evaluated in laboratory tests. Due to strong performance, the PATS+ and HAPEx Nano were advanced to the field test phase.

2. Milestone A: Cookstove Workshop. In order to understand the monitoring needs and constraints of the whole sector, a range of stakeholders including funders, manufacturers, researchers, and project implementers had to be brought together. Nexleaf and the World Bank convened a workshop in Delhi to discuss the possibility of achieving and scaling tier 4 performance using biomass fuels. A working group was formed to deliberate on the more difficult questions surrounding monitoring, resulting in the creation of a concept note.

3. Milestone 2: Field Deployment. StoveTrace continuous stove monitors (without $PM_{2.5}$ monitoring) were to be installed in 50 households to generate a set of stove usage data for analysis and identify any challenges in usage monitoring. StoveTrace sensors were deployed in 79 households, exceeding the goal by more than 50%. Sensors were deployed in Odisha, Tamil Nadu, Gujarat, and Maharashtra with seven partners on nine different stove types, and several critical insights were generated to inform stove design, program implementation, and guide the future development of StoveTrace sensors. PATS+ and HAPEx Nano sensors were deployed in 10 households in Notarpalli, Odisha, and both performed well, yielding correlations on the lower end of the normal range.

4. Milestone 3: Improved Climate and Health Metrics. Raw stove usage or indoor air pollution data alone does not convey the environmental and health impacts of clean cooking, so a set of algorithms were created in order to translate them into meaningful values. Based on improved stove usage data, the dashboard now displays the corresponding CO_2 equivalent (CO_2e) emissions reductions. Additionally, a framework for converting HAP to exposure was provided by Berkeley Air, and was built into the StoveTrace dashboard. Currently the dashboard can automatically convert raw $PM_{2.5}$ data into 24 hour averages and exposure reductions. Calculation of averted disability adjusted life years (ADALYs) is still performed manually, until further integration with HAPIT is achieved.

5. Milestone 4: Custom Extensible Analytics Dashboard. Although $PM_{2.5}$ is the primary driver of health impacts for domestic cooking, there are other significant contributors, such as carbon monoxide (CO). Other forms of data may require very different treatment, but the underlying structure of the StoveTrace dashboard should be built to accommodate them in the future. The underlying architecture of the StoveTrace dashboard was enhanced to facilitate the asynchronous processing of various data streams, beginning with modules for processing 24 hour exposure values from raw $PM_{2.5}$ data. This sets the stage for the development of other modules pertaining to CO and other pollutants and data streams.

6. Milestone 5: Integrated Sensor Platform Prototype Completion & Deployment. After suitable $PM_{2.5}$ sensors were identified, they had to be integrated into the existing StoveTrace platform. This entailed physical integration of the hardware, as well as backend processes for handling the new type of data. An integrated wireless sensor platform remotely monitors both improved cookstove usage (thermal sensors) and fine particulates ($PM_{2.5}$) with a modular design that makes it possible to add new sensors over time. The greatest logistical challenge of $PM_{2.5}$ sensors is the need for frequent zeroing, due to the drift they inevitably experience. Some solutions are proposed in this report, but have not been implemented. There are also now a set of algorithms that convert stove usage data into selected climate metrics based on estimated black carbon emissions that is now being used by two NGO partners in Odisha and Tamil Nadu for sending climate credit payments to rural women for their sensor-measured stove adoption.

A few other key achievements were made beyond the goals of this project:

1. Given the complexity of stove stacking, the continuous stove monitors have been attached to multiple improved cookstove models as well as traditional stoves, in order to measure **adoption as well as displacement** of traditional stoves with near-real time upload of the data.

2. Development has begun on the next generation of StoveTrace devices which are smaller, more affordable (less than $10), more durable, and non-cellular, thereby allowing them to be used anywhere, regardless of network availability.

3. A climate credit payment calculator has been built into the dashboard, making it easy to review and verify sensor data, and then calculate the climate credits earned by each household.

4. A CO bangle (developed by Intel and Nexleaf) was field tested in 15 homes among pregnant women to help them monitor the health of them and their child.

5. Indian Institute of Technology has been trained in Nexleaf's smartphone-based black carbon analysis method, and has analyzed nine stoves for black carbon that were previously never tested for this.

3. Building an Ecosystem for Results Based Financing

A diverse ecosystem of collaborating entities, from manufacturers to distributors and researchers to implementers, is necessary to ensure the successful and sustainable implementation of results based financing for clean cooking. Even within the monitoring and evaluation space, Nexleaf specializes in remote temperature sensor technology and recognizes the need to collaborate with organizations such as Berkeley Air, who are experts at air quality monitoring. As a result of this project, several key relationships have been strengthened that will serve to benefit the entire results based financing sector:

Berkeley Air
In February, 2016, staff from Nexleaf Analytics and Berkeley Air worked together to deploy StoveTrace and PATS+ side by side in the village of Notarpalli, Odisha. This marked the first time the organizations conducted field work together, and the first time $PM_{2.5}$ data had been gathered alongside StoveTrace data. Both teams were able to explain and demonstrate their respective technologies and discuss synergies for future collaboration. In particular, Nexleaf staff were holistically trained to conduct air quality measurements, enabling them to conduct further tests for this project independently. Both teams have begun discussing the need for a common API in the clean cooking space, so that technologies from different providers can communicate, allowing for more powerful data collection and analytics. A Nexleaf-Berkeley Air workshop took place on January 25th, 2017. Moving forward, Berkeley Air's role will be crucial in continuing to refine health metrics, for example, potentially to include health impacts on newborns due to long-term low-levels of carbon monoxide exposure for pregnant mothers, that can then be implemented in the open data platform and made available to all cookstove holders.

The Energy and Resources Institute (TERI)
TERI led the in-country $PM_{2.5}$ data collection and laboratory data analysis with support from Nexleaf and Berkeley Air. TERI's participation allowed for high quality, cost-effective field work, and a strong relationship with TERI's research team has been formed that will benefit future field testing of stoves and sensors of all varieties.

Household Air Pollution Intervention Tool (HAPIT)
Nexleaf has engaged in preliminary conversations with Ajay Pillarisetti, developer of HAPIT, to discuss potential synergies and methods for integrating platforms. Both parties agree that it would be advantageous for the StoveTrace dashboard to generate ADALYs using HAPIT, and more discussions are scheduled regarding the technical logistics, timelines, and funding this would entail.

Implementation Partners
Through this project, Nexleaf sensors have been deployed in Gujarat and Rajasthan with SEWA, Envirofit, AIREC (with Tata Trusts), and Dharma Life; in Odisha with Saunta Gaunta Foundation (SGF) and Sambhav; and in Tamil Nadu with Hand in Hand. Each deployment ranges between 5-34 sensors, and while relatively small, they have already generated immense interest and insight into the needs of stove usage monitoring among differing partners, geographies, and stove types (see section 6). With further input and iteration on the StoveTrace sensor, Nexleaf hopes to continue collaborating with all of these organizations.

Gold Standard Foundation (GSF)
Since May 2016, Nexleaf has participated in the expert working group convened by GSF to develop a methodology to quantify and verify the ADALYs of clean cooking interventions. Nexleaf was able to contribute some critical insights on the capabilities and limitations of

sensors, and the methodology is now out for public comment. Nexleaf has worked with GSF in the past on development of a black carbon methodology, and this continued collaboration only strengthens the relationship.

ISO
Since September 2014, Nexleaf has participated in the International Organization for Standardization (ISO) Technical Committee 285 (TC 285) to support the development of a standard for field testing of cookstoves. Nexleaf was able to take the lead in this standard development in Ghana in November 2015, and presented this document to the entire TC 285 group on January 5th, 2017. The standard includes guidance around both qualitative and quantitative measurements for cookstove monitoring for impact and understanding behavior change.

Monitoring for Impact and Behavior Change Working Group
Nexleaf has also assisted the World Bank in convening a working group to establish a set of guidelines for monitoring and evaluation in the clean cooking sector. Many organizations have participated, and a written methodology has been developed, but not approved, by the group. At this point, the overwhelming consensus is that the methodology must be field tested before further iteration can occur.

World Bank
The World Bank has been indispensable in facilitating collaboration between all of the aforementioned organizations, and many more. It is clear the World Bank holistically understands the needs of the sector, and is convening all of the right players to build something lasting. Nexleaf is grateful for the many introductions it has received, and is honored to be a part of this endeavor.

4. Milestone 1: Evaluation and Preparation

Sensor Selection

Nine commercially available $PM_{2.5}$ sensors were evaluated on the basis of cost, maximum detection limit, battery run time, potential ease of integration into the StoveTrace platform ("customizability"), and availability of proven results in published literature.

The selection criteria were as follows:

- **Cost**: Less than $500 per unit
- **Maximum detection limit:** Greater than 10,000μg/m^3
- **Battery run time**: Greater than one month (via internal or external power)
- **Customizability**: Able to send raw data directly to dashboard or via serial cable to ST5
- **Availability of proven results**: Available evidence of successful field deployments.

Ultimately three sensors met these criteria and were selected for testing: PATS+, HAPEx Nano, and AirBeam. A fourth sensor, TZOA, met these criteria, but was not available in time for the testing deadline. All of the evaluated sensors are pictured below, and detailed information is provided on the next page (Table 1).

Figure 1. Images of the nine sensors considered.

Device	Cost	Max Detection limits	Battery Run Time	Customizability	Other Notes	Selected?
PATS+	$500	50 mg/m^3	36 hours (can be powered externally)	Data transferred by UART	PATS+ has seen extensive field use by Berkeley Air Monitoring Group	Yes
HAPEx Nano	$120	150 mg/m^3	3-5 years (not rechargeable)	Data transferred by 4-pin cable	Only lab and preliminary field results available – nothing published	Yes
AirBeam	$249	0.400 mg/m^3	10 hours (can be powered externally)	Raw data available for download from AirBeam App*	*This turned out to be untrue and the data was not retrievable	Yes
TZOA	$400	"At least a few mg/m^3"	120 hours (can be powered externally)	Can send data by USB or FSC connector. Not Serial.	Devices were not available in time for testing	No
Alpha-sense	$440	Up to 10,000 particles/sec	No battery – requires power	Micro USB (programming), SPI (data)	Not selected due to lack of battery	No
SafeCast	$2,000	Up to 10,000 particles/sec	No battery – requires power	Unknown	Uses the Alphasense sensor. Not selected due to cost and lack of battery.	No
Speck	$200	0.640 mg/m^3	No battery – requires power	Can download data via USB or Speck's cloud server	Not selected due to low detection limit and lack of battery	No
Foobot	$75	1.6 mg/m^3	No battery – requires power	Can download CSV file from cloud server	Not selected due to low detection limit and lack of battery	No
Dylos DC1700	$425	Unknown	6 hours – requires AC power to charge	Can download via 9pin serial cable	Not selected due to AC power requirement and lack of customer service response	No

Table 1. Technical Specifications of the evaluated sensors.

Key Findings

Led by TERI with support from Berkeley Air, a laboratory testing protocol (Annex 1) was developed to evaluate the sensors' performance under ideal conditions. While good laboratory performance does not guarantee good field performance, any device which performs poorly in the laboratory can be summarily removed from consideration without field testing. The laboratory testing results are summarized below. The unabridged findings and detailed laboratory testing protocol can be found in Annexes 1 and 2, respectively.

•**Both the HAPEx Nano and PATS+ performed well in laboratory tests with concentrations reaching over 13,000µg/m^3, achieving R^2 correlations with the gravimetric gold standard of 0.80 and 0.97, respectively.** Of note, the PATS+ outperformed the supposed gold standard in real-time measurement, the GRIMM Aerosol Spectrometer. Additionally, PATS+ achieved a lower variance, with 6% Root Mean Square Error (RMSE) compared to the HAPEx Nano's 14%. Future analysis can explore the maximum tolerable RMSE to achieve sufficiently valid impact metrics. However, for now, both RMSE (and R^2) values are deemed sufficient.

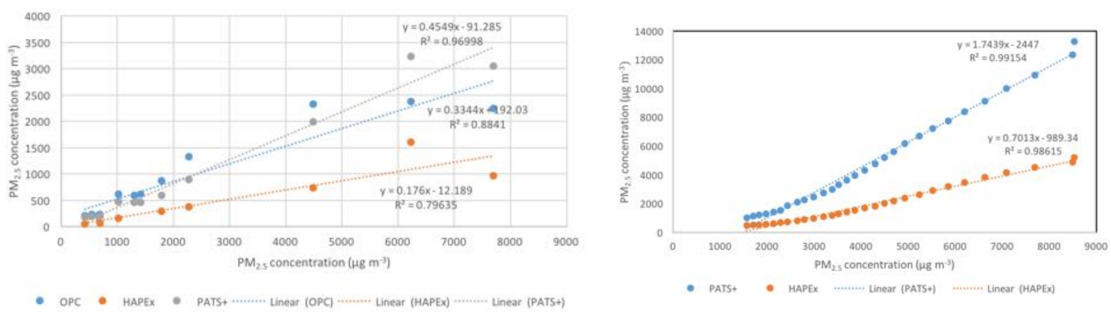

Figure 3. Left: Linear regression analysis plot for lab based validation of average $PM_{2.5}$ concentrations measured by sensors with gravimetric and OPC $PM_{2.5}$ concentration measurements. Right: Linear regression analysis plot for lab based validation of real time $PM_{2.5}$ concentrations measured by sensors and OPC.

•**Both HAPEx Nano and PATS+ displayed extremely strong correlation with real-time measurements, giving R^2 correlations of 0.99** with the GRIMM Aerosol Spectrometer.

•The AirBeam (not shown above) failed to give readings above $PM_{2.5}$ levels of 400µg/m3 (the sensor just continued to show 400µg/m^3), and the raw data was not retrievable from the AirBeam app, disqualifying it from further testing.

•Although the PATS+ demonstrated slightly superior performance, both devices fared well in laboratory trials. With other considerations such as cost leaning in favor of the HAPEx, there was no categorical winner and both devices were advanced to the field test phase.

5. Milestone A: Cookstove Workshop

On March 14th, 2016, Nexleaf and the World Bank convened a workshop in Delhi to discuss the possibility of achieving and scaling tier 4 performance using biomass fuels (see event flyer attached as Annex 3). Stakeholders were present from all aspects of the clean cooking industry, including manufacturers, distributors, NGOs, funders, and researchers (meeting minutes and attendance list is attached in Annex 4). Notably Joint Secretary Varsha Joshi from the Ministry of New and Renewable Energy for the Government of India attended and was extremely vocal in her support and input. She stated that clean cooking was the hardest possible challenge for India because there is no proper market for cookstoves yet. Since nobody knows exactly how to scale, it is exciting to see the World Bank and other partners devising a plan for scale. A day of vibrant discussion followed, with a remarkable level of introspection and honest dialogue about successes and failures.

Figure 4. Group discussion during the workshop.

Discussions focused on how to use the data and maintain quality while also developing a cost-effective solution. **The key points of consensus are summarized below:**

- The need to develop a sector-wide monitoring platform and methodology that can be utilized to produce reproducible and comparable results by all stakeholders.

- Capturing geographic variability is crucial, especially in India. More than six months is needed to cover all the seasons and potential changes in usage and stove performance over time (likely 12-18 months is needed).

- Sampling size must be large enough to be significant, but small enough to be cost-effective. A baseline is necessary, and rotational sampling might be useful for keeping costs manageable.

- Stove stacking must be fully captured and understood in order to properly position Tier 4 stoves; a single metric should focus on displacement of traditional stoves.
  User behavior will not fully be captured by quantitative stove usage data, so complementary qualitative metadata and socio-economic data capture through surveys is critical.

- Methods are required to combine qualitative data (or 'metadata') about the household and cooking conditions with the quantitative sensor data.

- There are three crucial use cases for the data, to inform: stove design, stove distribution, marketing & after-sales support, and results-based financing (for health and climate). **Underpinning all of these applications is stove usage data (of the improved and traditional stoves).**

During the discussion on monitoring for behavior change and impact, **it became apparent that a written methodology would be extremely beneficial for the sector, so Nexleaf convened a working group to develop the document** (outside the requirements of the project)**.** Fourteen members of the working group met by phone on June 15th, 2016, which resulted in the creation of a protocol for monitoring and evaluation of clean cooking interventions. Five members of the working group gave feedback on the document via email. The key points of the protocol are summarized below, and the full text is available in Annex 5.

- Key stakeholders in the cookstove sector including stove manufacturers, distributors, researchers, governments, and donors all participated to develop a common and open framework for ongoing monitoring, data collection, and reporting.

- The effort aims to quantify impacts in terms of adoption, ADALY's, and climate impacts.

- The framework provides standardized methodologies for collecting data in three thematic areas: data to improve stove design, data to improve Marketing, Distribution, Training, Post-Sales Service, and Monetizing benefits via Results-Based Financing.

- A novel aspect of the framework is the tiered sampling structure that enables more high-cost data to be collected from a smaller number of homes (i.e. exposure) to establish the range of impacts, and the validity and variability of the overall population to be collected in a larger number of homes using more cost-effective sensors (stove usage). See Figure 5 on the next page for a visual representation.

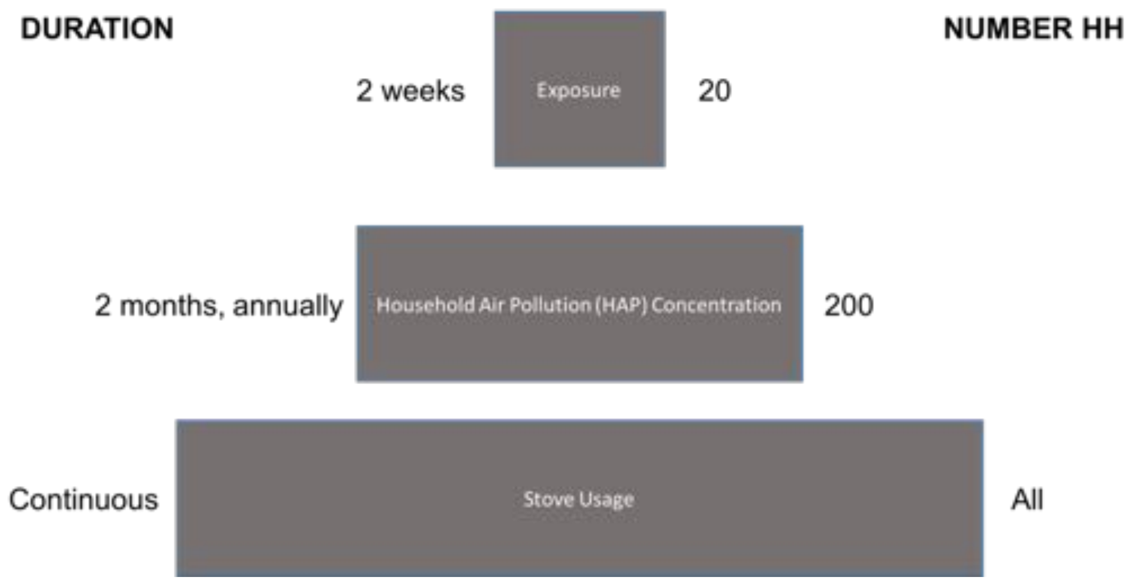

Figure 5. Example of the sampling framework for results based financing of health impacts.

6. Milestone 2: Field Deployment

StoveTrace sensors were deployed in 79 households, exceeding the goal by more than 50%. Sensors were deployed in Odisha, Tamil Nadu, Gujarat, and Maharashtra with seven partners on nine different stove types (see below for partners, stoves, and details of each deployment). Key insights:

1. Under ideal conditions, StoveTrace sensors give unprecedented insight into stove adoption and user preference (see key insights from each of the seven deployments below, based on collection of quantitative and qualitative data). For example, in the deployment in Keonjhar, Odisha (with SGF), StoveTrace verified greater than 95% displacement of mud stoves. Based on comparisons with other programs and stove models, this high adoption is likely attributable to the extremely user friendly stove design, the usage-based financial incentive (up to 360INR earnings per month), and rapid after sales service (repair or replacement guaranteed within 48 hours) which keeps user confidence in the program high.

2. Users are more likely to take care of sensors when payments are at stake (e.g. ensuring the probes and power cables stay plugged in and that the device does not get physically damaged). Households receiving climate credit payments show greater sensor up-time and a lower incidence of issues than those without. For instance, in the village of Notarpalli (sample size 35), climate credit payments began on August 17th, 2016, and the percentage of sensors not sending data decreased from 64.4% in August 2016 to 19.1% in November 2016.

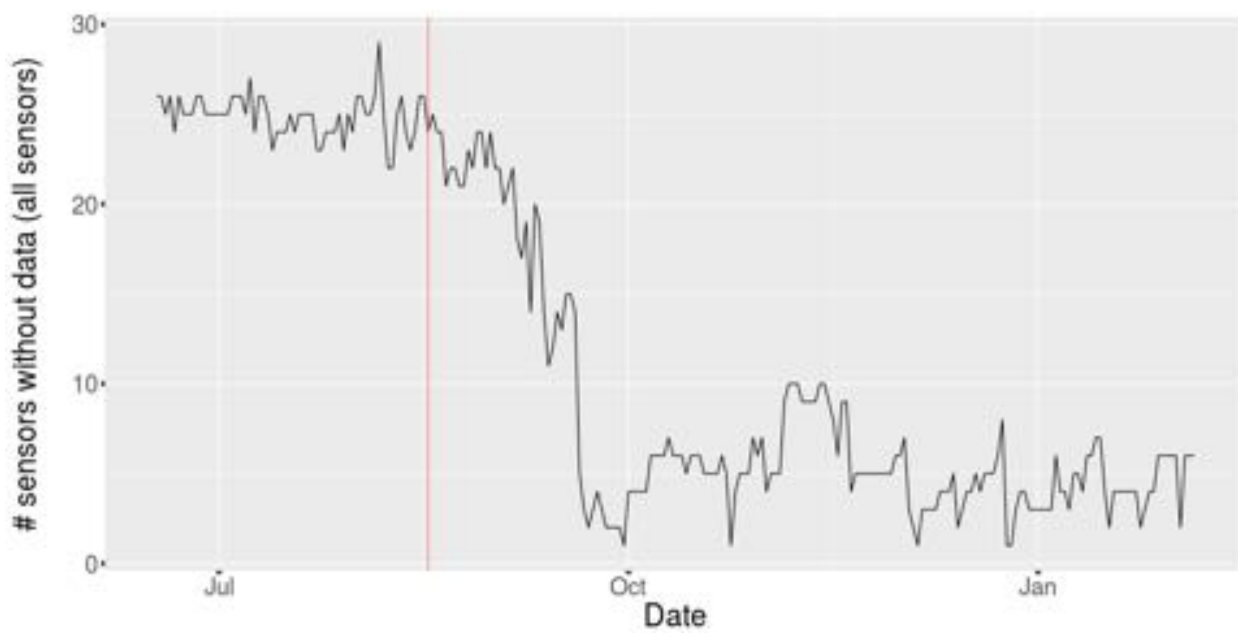

Figure 6. Number of sensors in Notarpalli which did not send any data each day. The red line on August 17th the date when climate credit earnings were introduced. The large drop in sensor downtime over the next month and a half is almost certainly attributable to this, though improved diligence in resolving issues likely also contributed.

3. In discussions, users in Odisha expressed a strong preference for large, side-loading stoves. In Notarpalli, six households switched from the comparatively small Biolite HomeStove to the Greenway Jumbo stove, and average usage rose from 10.3 minutes per day to 2.3 hours per day – a 13-fold increase.

4. Stove stacking is an incredibly complex phenomenon to monitor and study quantitatively. More than 10 types of stoves were encountered in households (mud stove, LPG, induction stove, kerosene stove, and six varieties of improved biomass cookstove). Almost any permutation of the aforementioned stoves may be present in a household, in different locations, of different shapes, and different usage patterns. Without monitoring every single stove in a household, it is impossible to see the full picture of cooking behavior, and significant sources of greenhouse gases and indoor air pollution can be missed – just one dirty stove could comprise the majority of emissions in a household. Additionally, some of these stoves, notably LPG and mud stoves, are very difficult to monitor accurately at all. **The implication is that StoveTrace hardware must be capable of simultaneously monitoring myriad stoves in a household without inconveniencing the user.** A small, wireless, battery operated sensor that is able to mount on a variety of stoves would achieve this goal. The ST5's many power and probe cables would be too cumbersome and would be quickly unplugged by users.

5. Both the HAPEx and PATS+ performed well in the field, giving R^2 correlations with gravimetric analysis of 0.75 and 0.74, respectively. PATS+ displayed lower variability, but had problems with battery life (sometimes lasting less than 12 hours, which was remedied by powering it directly with a solar panel). Battery life was no issue for the HAPEx, but an unknown error caused by long-term deployments erased all data. Though the exact cause was never identified, new generations of the HAPEx do not have this issue. Both devices showed promise and with no clear winner, both were advanced to the integration phase.

6a. Continuous Stove Monitoring: Detailed Findings from Field Deployments

Dharma Life

Nine Mimi Moto stoves were equipped with StoveTrace sensors, with additional monitoring of the traditional mud in two homes (the mud stove was not monitored in the others due to physical constraints). There was strong adoption of the Mimi Moto among all households in the first week, with an average of 6.7 cooking events per household and no households below three. However, by the end of the first month, high usage was sustained in only two households (average of 7.5 cooking events in the last week of the month) with lower usage in the other seven (average of 0.8 cooking events in the last week of the month). All households had discontinued usage of the Mimi Moto after one and a half months, at which point it was learned they had exhausted their supply of pellets, which were then resupplied.

To accommodate the Mimi Moto's removable combustion chamber, the StoveTrace probe was attached to the side of the stove with a screw. This placement has worked well, but some cooking events have not been detected due to low temperatures. Improved placement, and training of the StoveTrace cooking detection algorithm on the Mimi Moto could summarily resolve this issue.

Figure 7. Left: Mimi Moto and StoveTrace sensor inside household. Right: dashboard visualization showing all households in the deployment. All stoves shown are Mimi Motos, with just one mud stove (in red rectangle).

AIREC

StoveTrace sensors were deployed in six households in Gujarat. These households showed the most complex stove stacking encountered, frequently possessing two to three mud stoves, Envirofit stove, plus a kerosene stove and/or LPG stove. Due to material constraints, in each house between 1-4 stoves were monitored. Usage of the kerosene stoves ranged from 0.1 to 3.5 hours per day, averaging 1.0 hours per day. Usage of the Envirofit stoves ranged from 0 to 3.7 hours per day, averaging 1.8 hours per day. Despite high usage of the Envirofit and kerosene stoves, the mud stove remains in very widespread use. Since an algorithm has not yet been developed to detect cooking on TCS, this widespread use was determined by manual inspection of temperature plots.

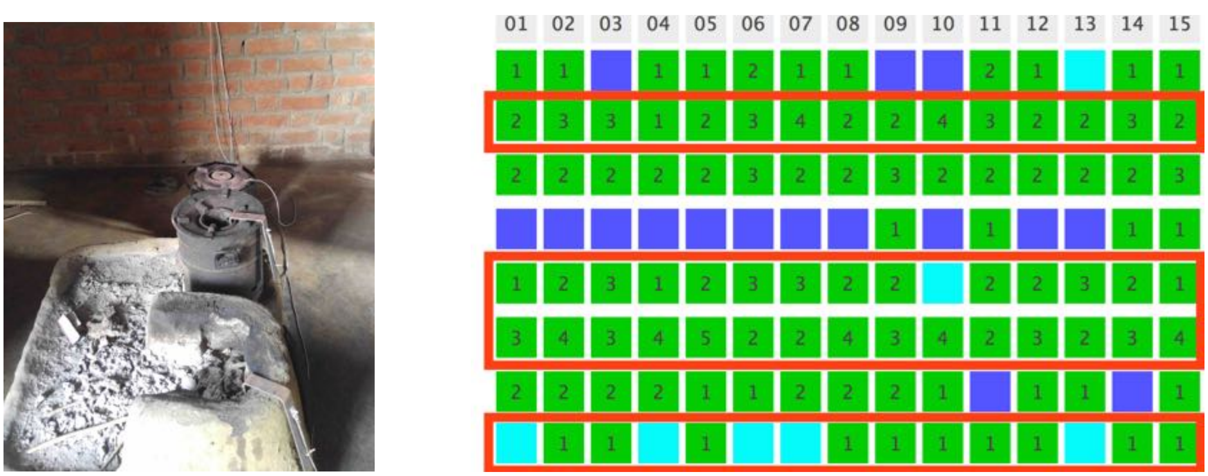

Figure 8. Left: Mud stove, Envirofit ICS, and kerosene stove simultaneously monitored by StoveTrace. Right: dashboard showing active usage of every stove type, with mud stoves highlighted in red.

Envirofit
StoveTrace sensors were deployed in five households in Maharashtra, monitoring only the ICS. This deployment posed a number of challenges, from poor cellular signal, difficult accessibility for the technical staff, and rough conditions (even including destruction of one sensor at the hands of a monkey). These challenges highlight the need to make the StoveTrace hardware more robust, even though Envirofit was very proactive about addressing issues whenever possible. From the data that is available, it is evident that four of five households were consistent users of the Envirofit stove, averaging 1.3 cooking events per day, though it should be noted that this was not a random sample (Envirofit selected the households to be monitored).

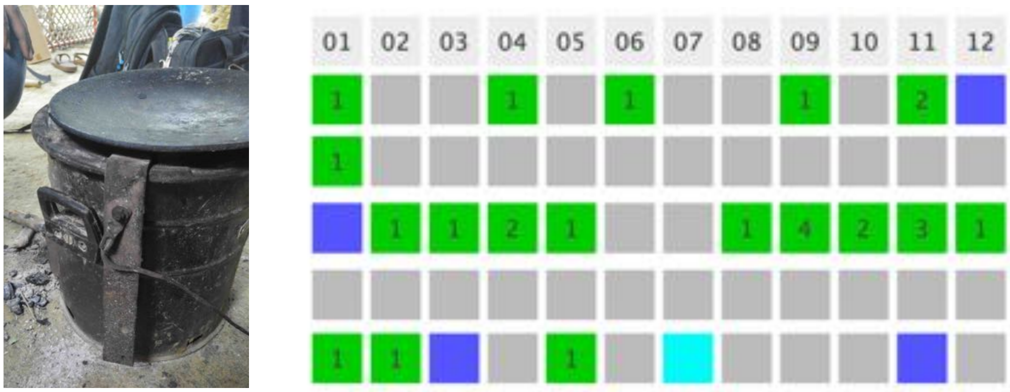

Figure 9. Left: Envirofit PCS-1 with StoveTrace probe. Right: Dashboard visualization showing the intermittency of data in this deployment due to a host of challenges.

SEWA
In this novel deployment, five StoveTrace sensors were placed on LPG stoves in Gujarat (not originally stipulated in the project). This trial demonstrated the potential for monitoring LPG stoves, but revealed a host of new challenges. High temperatures frequently destroyed the probes. As LPG stoves are quite lightweight, some users tended to move them around the kitchen, making the sturdy and unobtrusive placement of the probe quite difficult.

Another difficulty with monitoring LPG stoves is that the rapid on/off cycles of the stove were frequently undetectable by the hardware set to log data every 10 minutes. The graph below shows four apparent cooking events which were not caught by the detection algorithm.

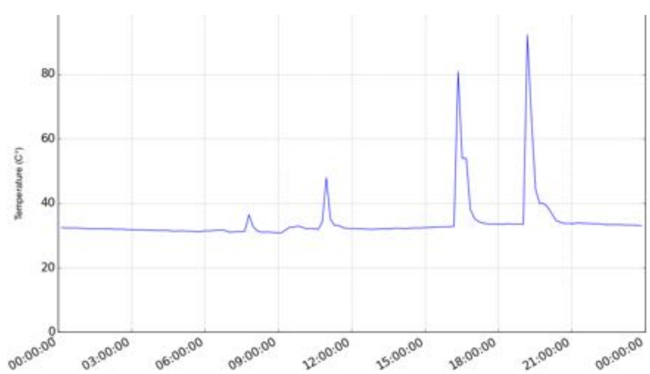

Figure 10. 24 hour temperature chart of the LPG stove, showing four apparent cooking events that were of insufficient duration to be detected by the cooking detection algorithm.

The earlier two events only show elevated temperature for one data point, and the sample did not happen to be taken at a point in time where the temperature was high enough to be considered cooking (probably in the initial minutes of the cooking event). The latter two events show temperatures high enough to be considered cooking, but did not trigger the cooking event detector because they are too short. In order to accurately detect cooking on LPG stoves, it will be necessary to sample at a higher frequency, and very likely necessary to develop a new detection algorithm to account for the fundamentally different characteristics of LPG fires versus biomass fires. **Further work is needed to achieve reliable monitoring of LPG stoves, but this small pilot has served as a proof of concept.**

Figure 11. Left: StoveTrace probe placed on the LPG burner. Right: dashboard visualization of the deployment. Note the high numbers in the last days of the penultimate row which indicate a destroyed probe (due to high temperatures).

Keonjhar, Odisha

Nexleaf has deployed StoveTrace sensors on Greenway Jumbo stoves and mud stoves in ten households in Keonjhar, Odisha. With ideal conditions including excellent cellular network coverage, easy accessibility, and strong community engagement, this deployment has proceeded nearly flawlessly and serves to demonstrate the full capability of the StoveTrace platform. Across the board, households have nearly completely discontinued use of their mud stove, and are cooking an average of 4.25 hours per day on the ICS. Users in this community receive climate credits for their CO_2 and black carbon reductions at a value of $12/ton, which certainly affects their cooking behavior and caretaking of the sensor (which can be considered an income generating asset). The incidence of sensor issues in this community has been remarkably low, with only three probes needed replacement in the first two months.

Figure 12. Left: Users' own stove usage data is shown to them to prompt a discussion about clean cooking. Right: perfectly consistent data on the dashboard (mud stove data highlighted in red).

Nayagarh, Odisha
The largest single StoveTrace deployment, sensors have been placed on ICS and mud stoves in 34 households in the village of Notarpalli. Nexleaf has built a very strong relationship with the women in this community, and their feedback on sensors, stoves, and climate credit payments has been invaluable. Key insights from Notarpalli have been the preference for side-loading, extra large stoves capable of holding pots that can cook for 10+ people. Users have been delighted with the Greenway Jumbo stove and NDMI PMU0414D, whereas smaller and/or top-loading stoves have been outright rejected. Of the six Biolite stoves which were originally in place, all but one have been replaced at the user's request with Greenway stoves. The Greenway Jumbo stoves (n = 27) are used for an average of 3.3 hours/day, while the NDMI PMU0414D stoves (n = 6) are used for an average of 2.23 hours/day.

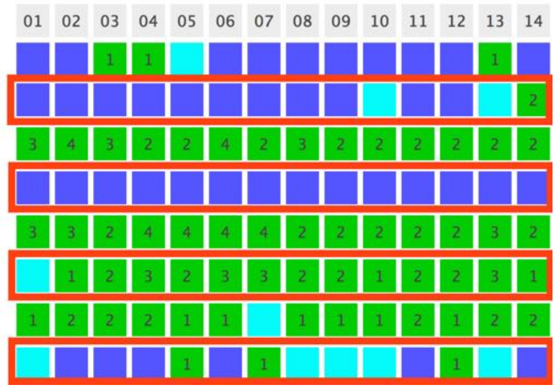

Figure 13. Left: Users gather for the M-Pesa training. Right: Dashboard visualization, with mud stoves in red.

Vettaikarakuppam, Tamil Nadu
StoveTrace sensors are being used to calculate climate credits for ten households in Tamil Nadu, several hours outside of Chennai, showing average cooking time of 1.9 hours per day on improved cookstoves. Some delays in setting up the mobile money accounts for users (e.g. rejected application forms) have highlighted challenges in the mobile money signup process and the need to complete signups months before payments are to be made.

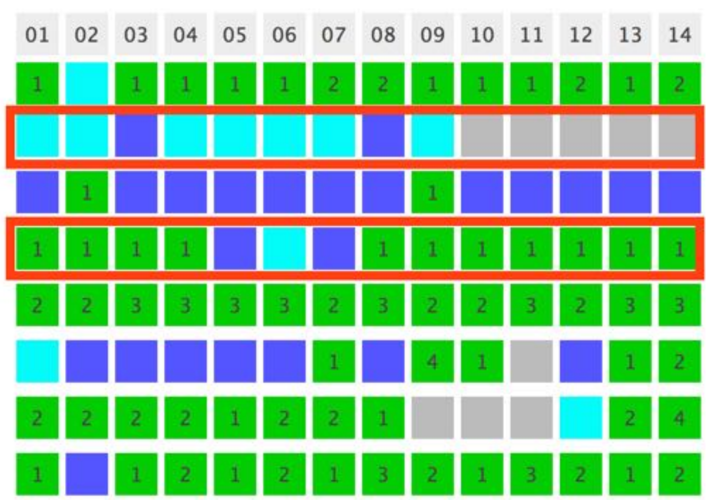

Figure 14. Left: Newly installed stove. Right: Dashboard visualization (mud stoves highlighted in red).

6b. $PM_{2.5}$ Field Tests: Detailed Field Deployments

After passing the laboratory tests, the HAPEx and PATS+ were advanced to field trials. Thirty-eight samples were collected from households in the village of Notarpalli, Nayagarh District, Odisha, India. The homes in Notarpalli are simple mud wall huts with thatch or tile roofs, frequently with an enclosed or three-wall kitchen. Every home possessed one traditional mud stove and one improved cookstove. Through these field tests, the real-world accuracy, durability and usability of the sensors was evaluated. Product specific field deployment protocols were created for the PATS+ and HAPEx, and can be found in Annexes 6 and 7, respectively. Sampling forms are found in Annex 8.

Key Findings

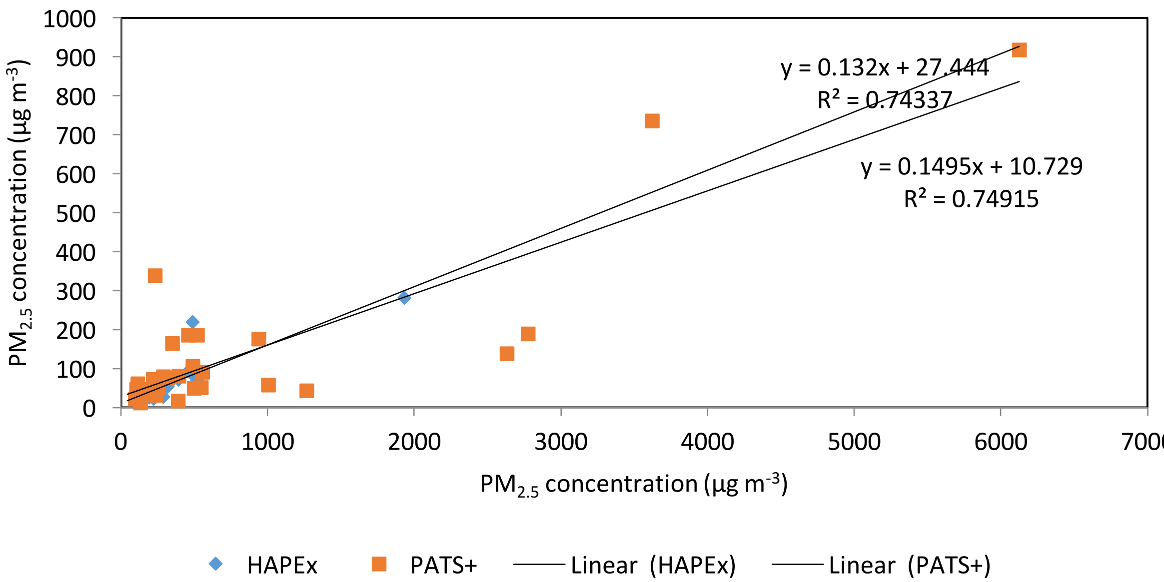

Figure 15. Plot of HAPEx and PATS+ vs gravimetric data from households in Notarpalli.

•HAPEx and PATS+ exhibited similar performance, yielding R^2 correlations with the gravimetric gold standard of 0.75 and 0.74, respectively. HAPEx achieved a normalized RMSE of 18%, compared to the PATS+'s 11%, indicting slightly better precision from the PATS+. These similar results are interesting in contrast to the laboratory tests, where the PATS+ performed markedly better. According to Berkeley Air, these values are on the lower end of the normal range of r^2 values for field tests, which is usually between 0.75-0.95, and are acceptable.[1,2,3,4] This may be attributable to the use of shorter than normal 12 hour samples, leading to greater variability than longer 24 or 48 hour samples.

•The PATS+ performed well at $PM_{2.5}$ concentrations above 500µg/m^3 (R^2 = 0.82), it showed remarkably worse performance below that threshold (R^2 = 0.16). There was not enough data to

[1] Rosa G, Majorin F, Boisson S, Barstow C, Johnson M, et al. (2014) Assessing the Impact of Water Filters and Improved Cook Stoves on Drinking Water Quality and Household Air Pollution: A Randomised Controlled Trial in Rwanda. PLoS ONE 9(3).
[2] Chowdhury, Z., Edwards, R.D., Johnson, M., Shields, K.N., Allen, T., Canuz, E., Smith, K.R., 2007. An inexpensive light-scattering particle monitor: field validation. Journal of Environmental Monitoring.
[3] Huboyo, H.S., Tohno, S., Lestari, P., Mizohata, A., Okumura, M., 2013. Characteristics of indoor air pollution in rural mountainous and rural coastal communities in Indonesia. Atmospheric Environment.
[4] Cynthia, A.A., Edwards, R.D., Johnson, M., Zuk, M., Rojas, L., Jiminez, R.D., Riojas-Rodriguez, H., Masera, O., 2007. Reduction in personal exposures to particulate matter and carbon monoxide as a result of the installation of a Patsari improved cook stove in Michoacan Mexico. Indoor Air.

determine the HAPEx's performance above 500μg/m^3, but it outperformed the PATS+ under 500μg/m^3 (R^2 = 0.63).

•HAPEx's superior battery life eliminated the need for an external power source and made deployments much more reliable.

•PICA (the PATS+) software was more difficult to use and prone to crashing than HAPEx's, but gave more customizability for data collection.

•An unknown error after extended length deployments rendered the HAPEx units defunct, and unable to collect further data (hence the lack of high concentration data). This issue has been resolved in the new model.

7. Milestone 3: Improved Climate and Health Metrics

The strongest and most clearly measureable link between stove usage and illness is exposure to $PM_{2.5}$. The adverse health impacts of $PM_{2.5}$ are a function of overall – not momentary – exposure. In other words, the health impact is determined by the average $PM_{2.5}$ exposure level over a given time period, regardless of the various transient fluctuations in $PM_{2.5}$ exposure levels during that period. Typically, the average exposure is calculated over 24 hours.

ADALYs are a mechanism for quantifying the burden of disease and early death which is avoided through a given intervention. The amelioration of respiratory and other illnesses through the use of clean cookstoves can therefore be quantified in the form of ADALY's. ADALY's are calculated using the Household Air Pollution Intervention Tool (HAPIT), which draws upon extensive epidemiological data from the Global Burden of Disease studies. Pre- and post-intervention $PM_{2.5}$ exposure levels are the sole inputs to HAPIT. These are *personal exposure* values which can only be measured with expensive and cumbersome equipment worn by the stove user. However, approximations can be made.

A framework for converting HAP to exposure was provided by Berkeley Air (see Annex 9). The primary female cook's exposure is calculated as 74.2% of HAP. Men's and young children's personal exposures are calculated as 45% and 62.8% of HAP, respectively (Balakrishnan 2014).[5] Special consideration had to be given while building the algorithm into the dashboard due to the nature of long-term sensor deployments, which are discussed in section 9.

The dashboard automatically applies the conversion to the raw $PM_{2.5}$ data to obtain a daily average $PM_{2.5}$ exposure value by sensor. Each sensor is associated with a household and is therefore able to track the personal $PM_{2.5}$ exposure of household residents over time. Prior to a given intervention, the sensors can be deployed to generate baseline exposure levels, which will be compared to post-intervention measurements for the calculation of ADALYs in HAPIT.

With the approximated daily $PM_{2.5}$ exposure values, the dashboard automatically calculates the average $PM_{2.5}$ exposures over the selected timeframe and the percent reduction from baseline. ADALYs generated during the selected time period and the total ADALYs generated to date are also displayed, but must be input manually. Currently, the dashboard does not communicate directly with HAPIT. Foreseeably, HAPIT can implement an open API, allowing for automatic computation of ADALYs on the StoveTrace dashboard updated every 24 hours.

Data from the first phase of $PM_{2.5}$ sensor field tests was used to demonstrate the generation of ADALYs using the StoveTrace dashboard. The results are presented as proof of concept only, and must not be considered proof of impact, as they comprise only single 24 hour samples for each household, and are compared against a literature baseline for rural Odisha which may not necessarily reflect actual pre-intervention indoor air pollution levels in this particular village (Balakrishnan 2013).[6] Using the baseline of 467μg/m^3, the $PM_{2.5}$ sensors show an average exposure reduction of 80%, with a range from 59%-93% reduction. This corresponds to a one day, per household average ADALY of 0.000170, with a range of 0.000077 to 0.00031.

Furthermore, due to the new modular architecture of the StoveTrace dashboard (see next section), as health metrics improve, the system can easily be updated with them.

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[5] Balakrishnan, K., Mehta, S., Ghosh, S., Johnson, M.A., Brauer, M., Naeher, L., Smith, K.R., 2014. WHO Guidelines for Indoor Air Quality: Household Fuel Combustion - Population levels of household air pollution and exposures.
[6] Balakrishnan, K., Ghosh, S., Ganguli, B., Sambandam, S., Bruce, N., Barnes, D.F. Smith, K.R., 2013. State and national household concentrations of PM2.5 from solid cookfuel use: Results from measurements and modeling in India for estimation of the global burden of disease.

8. Milestone 4: Custom Extensible Analytics Dashboard

The results-based financing open data platform can be accessed from www.stovetrace.org using any web browser. The underlying architecture of the StoveTrace dashboard was enhanced to facilitate the asynchronous processing of various data streams, beginning with $PM_{2.5}$. This is achieved by sorting the data through various dedicated modules, which enables the platform to scale, since large quantities of data can be handled by the appropriate module. For example, the conversion of raw $PM_{2.5}$ data into personal exposures values as described in the previous section is sorted into the HAPIT and ADALYs workflow and parsed into the following modules:

1. Detection and analysis of the zeroing events
2. Application of zeroing corrections
3. Application of additional calibration/correction adjustments per device
4. Application of correction adjustments per region
5. Conversion of $PM_{2.5}$ HAP concentration to exposure

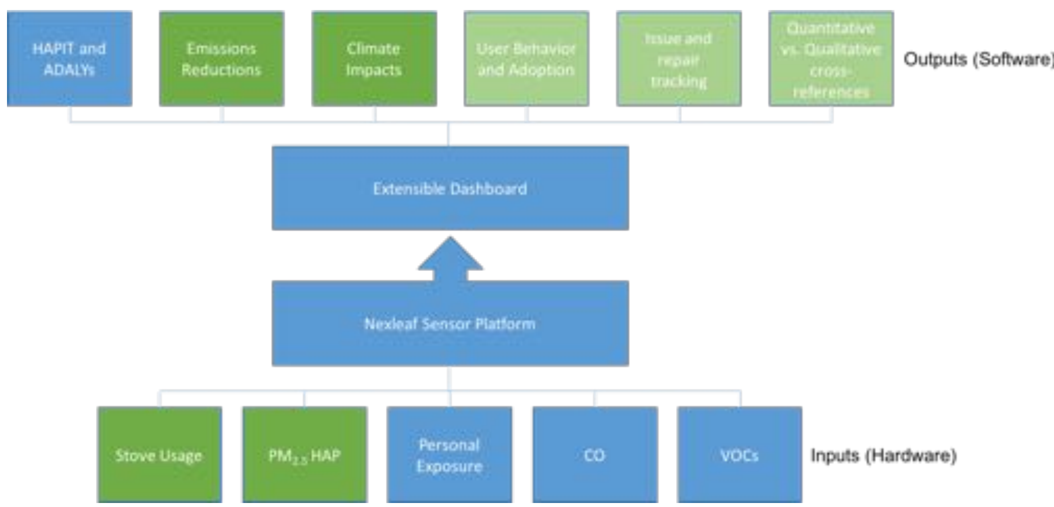


Figure 16. A conceptual block diagram of the various modules which can be implemented with the dashboard's new extensible architecture. Blocks in dark green have been built, and those in light green are under development. Modules in blue have not yet been built.

Currently, $PM_{2.5}$ data is displayed as a single chart showing data in 24-hour increments. Any HAPEx or PATS file can be uploaded either automatically in near real-time by a StoveTrace-enabled $PM_{2.5}$ device or manually via the admin portal.

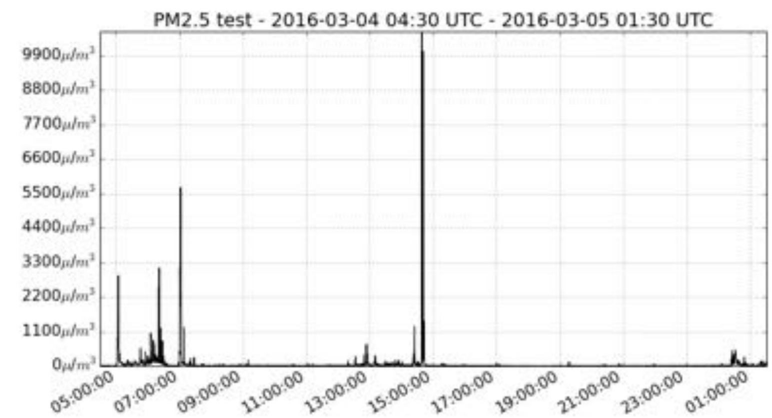


Figure 17. Current display of $PM_{2.5}$ data on the dashboard.

With further development, the data can be overlaid with stove usage (displaying both data sets on a dual-axis plot) and represented in the calendar grid (see mockup below). This will make visual comparison of stove usage and $PM_{2.5}$ data very easy for the viewer.

Figure 18. Mockup of the visualization of $PM_{2.5}$ data (thin line) adjacent to stove usage (square).

Figure 19. Health metrics as displayed on the dashboard. Note that as integration with HAPIT has not yet been implemented, those field appear blank for now.

9. Milestone 5: Integrated Sensor Platform Prototype Completion & Deployment

As both the HAPEx and PATS+ demonstrated good performance in the field, but had different strengths and weaknesses, there was no categorically superior device. Furthermore, as there could be unique challenges integrating either device into the StoveTrace platform, both were advanced to the hardware integration stage. Due to availability, four integrated HAPEx-StoveTrace devices, and six PATS-StoveTrace integrated devices were built.

The goal of integrating $PM_{2.5}$ into StoveTrace is to create a stand-alone online exposure monitoring tool, but existing $PM_{2.5}$ sensors are not self-contained: they require significant human-driven processes in terms of physical interaction and data analysis. Firstly, sensors must be calibrated in a laboratory – this can be thought of as "training" the sensor to give accurate readings for different types of smoke. Next, gravimetric instruments must be deployed alongside the sensors in households as a ground truth, and the filters sent back to the laboratory for analysis, which generates a correction factor. Lastly, the sensors must also be zeroed approximately once per week. Zeroing a sensor is the process of taking measurements in a completely particulate-free environment in order to establish an accurate baseline.

These results of these processes must be reflected in the data handling. The calibration and correction factor must be applied to the sensor data, and zeroing events must be noted. Normally this is done manually in spreadsheets. The ADALY module workflow described on page 24 demonstrates the various automated processes

The greatest logistical challenge of $PM_{2.5}$ sensors is the need for frequent zeroing, due to the drift they inevitably experience. Zeroing requires the device to be placed in an airtight container with completely clean air (achieved by passing several liters of air through a HEPA filter embedded in the container). $PM_{2.5}$ sensor deployments typically last only 24-48 hours, during which period the drift is nominal, permitting zeroing to be performed only before and after the deployment.

The HAPEx and PATSmini (a pared down version of the PATS+, see page 28 for more detail) take different approaches to zeroing. The HAPEx zeroes by creating an offset value and applying it to all data. For example, if the HAPEx is placed inside the zero box with filtered air and records 5μg/m^3, then that is set as the baseline and 5μg/m^3 will be subtracted from all subsequent measurements, until it is re-zeroed. The developer of the HAPEx, Climate Solutions, recommends zeroing the device at least once every week. The PATSmini does not create an offset. Rather, a zero must be performed both before and after each sampling period, and the sensor applies a linear correction to the entire sampling period contained between the zeroing periods.

The goal of integrating $PM_{2.5}$ sensors into the StoveTrace platform is to enable long-term $PM_{2.5}$ monitoring with minimal human intervention. To reach scale, the devices will ideally operate for months without any intervention. At the present stage of development, the $PM_{2.5}$ sensors will simply need to be manually zeroed, by a technician, at least every week to compensate for drift and maintain data accuracy. Additionally, the integrated $PM_{2.5}$ sensors have wires extending to the ST5, such that they cannot be contained inside a typical zeroing box. A new zeroing box will need to be designed that maintains an airtight seal even with the wires sticking out, or an approach that detaches the sensors and still performs a correct zeroing operation must be devised.

To be scalable, technician visits must not be necessary. As more data is collected, Nexleaf will determine if any automated zeroing processes and analytics could be applied to compensate for drift. This will require considerable amounts of data, collected over long durations in experimental field setups with consultation/review from the sensor developers. Climate Solutions has suggested that it may be possible to implement automated zeroing without the airtight enclosure by conducting them very early in the mornings (ideally around 4:00 or 5:00am) when $PM_{2.5}$ levels in the kitchen tend to be lowest. Zeroing events could be triggered automatically by the ST5 – an innovative feature that is not available to the standalone unit. A study could be conducted on $PM_{2.5}$ levels in the kitchen during the night, and if an average value can be determined with high confidence, then that can be deducted from the nightly measurements to zero the sensors in each household. Development of such a method is beyond the scope of this project, but is a logical next step, necessary for these sensors to be useful in real world settings.

A further complication with long-term collection of $PM_{2.5}$ data is how to deal with missing data. Room $PM_{2.5}$ concentrations spike during stove usage, such that a data outage during the time of stove usage could cause daily concentrations to be underestimated, or conversely a data outage at times when the stove is not in use could cause concentrations to be overestimated. Under the assumption that data outages are not correlated with cooking events, however, averages over many days should present a good estimate of longer-term concentrations. An advantage of integrating the $PM_{2.5}$ sensor with the StoveTrace device is that people who are receiving carbon-credit payments for cooking are incentivized to keep the StoveTrace device attached and functioning, which promotes consistent $PM_{2.5}$ data as well.

HAPEx Nano

Climate Solutions provided Nexleaf with customized HAPEx units which replaced the micro-USB port with a 4 pin header to simplify cabling for prototype developing. The HAPEX has its own non-rechargeable internal battery, but can also be powered directly from the ST5 between 3V to 5V. Communication between the ST5 and HAPEx occurs via 3.3V TTL, and the communication protocol is a combination of ASCII commands from StoveTrace and binary responses from the HAPEx. StoveTrace configures the sampling interval and puts the HAPEx into its mission mode. The HAPEx will log samples at the configured interval and return those logged samples as StoveTrace requests them.

StoveTrace stores the readings from the HAPEx locally on its SD card. Every hour StoveTrace uploads the stored readings to the StoveTrace backend via the data connection on the cellular network. If it is unable to upload the data due to poor cellular connectivity, it will try again in an hour, repeating this process until the data can be uploaded.

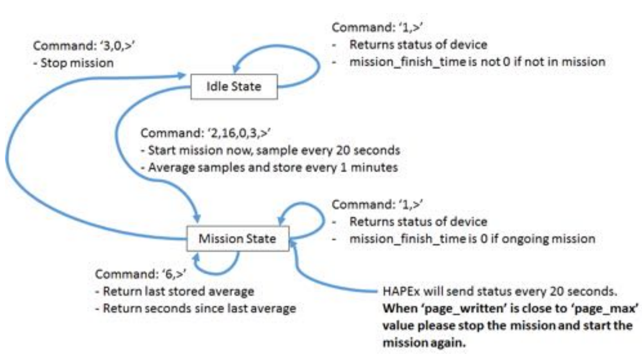


Figure 20. Left: Communication diagram showing the commands sent between the ST5 and HAPEx. Right: close up of the custom-made ports for interfacing with StoveTrace.

PATS

The PATS+ has a number of features that would be redundant when paired with the ST5, such as internal clock, power supply, and SD card logging capabilities. Therefore, a custom unit, the PATSmini, was created to reduce complexity and cost. The PATSmini is smaller and the most significant reductions are the removal of the battery and the logging to an SD card.

The PATSmini does not have an internal battery so it must be powered by StoveTrace or an external power source between 3.3V to 5V. Like the HAPEx, communication with the PATSmini occurs via UART at 3.3V. The PATSmini communication protocol is a combination of ASCII commands from StoveTrace and either binary or ASCII responses from the PATSmini. StoveTrace puts the PATSmini into its acquisition mode using a command and periodically (every 5 minutes) requests a single data record. The PATSmini is constantly sampling and when the data record is requested, it will average and return the $PM_{2.5}$ measurement since the last request. Readings from the PATSmini are stored and uploaded by the ST5 in the same manner as with the HAPEx.

Figure 21. Close up image of the custom made PATSmini.

Field Testing

Following the product specific deployment protocols, the integrated HAPEx and PATSmini devices were deployed in a total of ten households in the village of Notarpalli, Odisha. The $PM_{2.5}$ sensors had lengthy cables connecting them to the ST5's, and were simply hung approximately 1.5 meters above the ground and 1.0 meter horizontally from the center of the improved cookstove. There were no difficulties with the physical placement.

Figure 22. Images of the integrated devices deployed inside households.

Stove usage and indoor $PM_{2.5}$ levels were simultaneously monitored and, as shown in the chart below, there is a clear relationship between the two, with spikes in stove temperature and $PM_{2.5}$ levels occurring at the same time. However, an investigation of a potentially statistically significant correlation has not yet been performed.

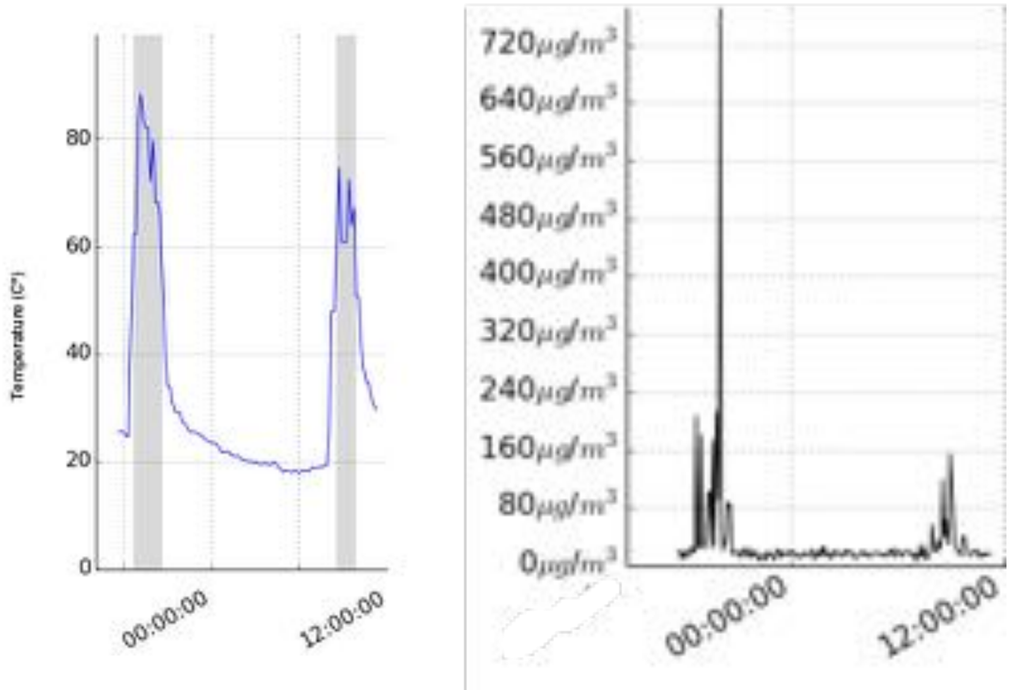


Figure 23. Left: stove usage data over a 12 hour period showing two clear cooking events. Right: Indoor $PM_{2.5}$ levels measured by the integrated PATSmini in the same household over the same duration, clearly showing two $PM_{2.5}$ spikes corresponding to the cooking events.

Note: because these devices have not been zeroed, the data cannot be used to draw conclusions about actual indoor $PM_{2.5}$ values or health impacts.

10. Auxiliary Developments

In the course of this project, several new features, not covered above, emerged as logical extensions of this work, and are currently in various stages of development.

<u>Software</u>

Payments Platform – Finished

Imperfect data presents a severe challenge when calculating usage-based payments. For example, if the temperature probe malfunctions and gives inaccurate readings, the user's payments cannot be accurately calculated. To resolve this, Nexleaf added a payment calculation portal to the dashboard, which allows an administrator to quickly visually validate the cooking durations as determined by the detection algorithm, and override/adjust them if needed. The values for each day (calculated and adjusted) are displayed in parallel with the chart, which can be expanded for visual inspection by hovering the computer mouse over the desired section.

For days where data is unavailable or unreliable (such as a burnt-out temperature probe), the payment calculator automatically credits the user with an amount equal to the average cooking duration over the last 30 days.

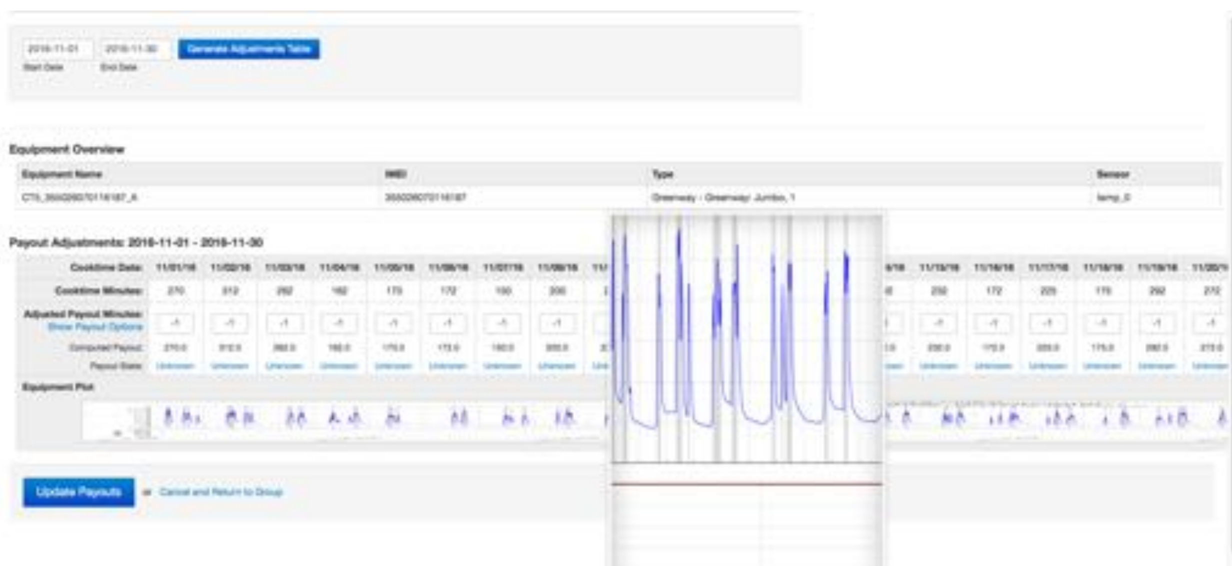


Figure 24. Screenshot of the payment calculator on the StoveTrace dashboard showing the magnification of a certain portion of the temperature plot for easy viewing and adjustment

Group Summary – In Development

As the size and complexity of deployments grew, it was clear that a way to automatically generate certain group statistics was necessary (for example, what is the average daily cooking duration of users on a particular stove model?). Thus the Group Summary page was created, which automatically shows the number of homes which are actively cooking, histogram of average daily cooking duration for all households, total number of hours cooked and climate credits earned, climate impacts, and health impacts (when $PM_{2.5}$ sensors are also installed).

Furthermore, the data can be cross-reference by deployment, stove type, household size, and cooking level (low, medium, high). For other analyses that one may wish to perform, the raw data can be exported into CSV files.

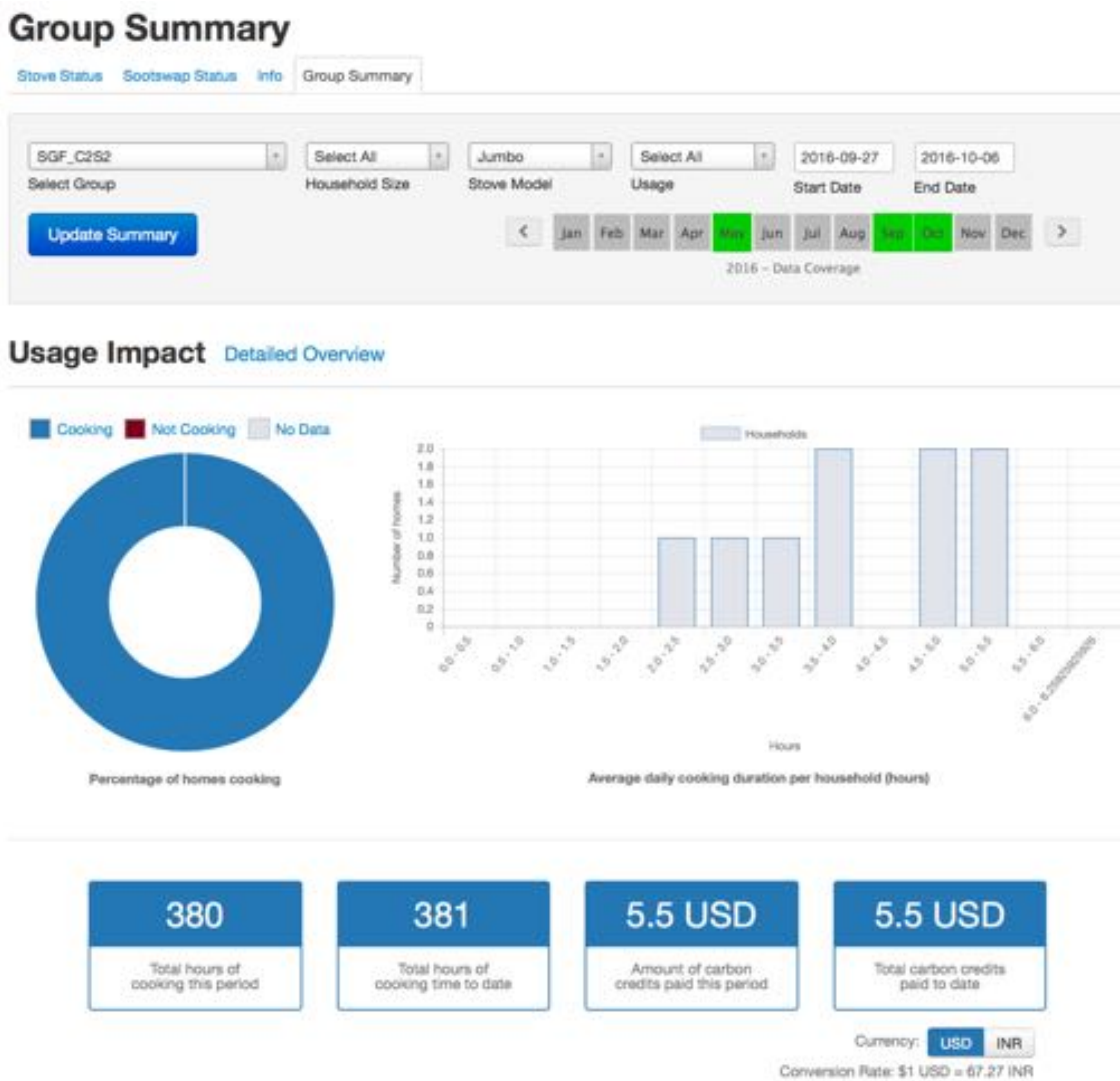


Figure 25. Group summary statistics for a deployment, including the percentage of homes cooking, a histogram of average cooking duration, total hours of cooking, and climate payments paid.

Issue Tracking – Conceptualization

Given the frequency of technical issues with both StoveTrace sensors and improved cookstoves, a system for tracking problems and their resolution was clearly necessary before scale can be achieved. This system will consist of a smartphone app that prompts field staff through the troubleshooting process, logs their maintenance actions, and displays them on the dashboard. For example, the system would record if a sensor was replaced or if the combustion chamber of a stove was repaired, and program staff could view this from anywhere in the world.

Not only will this ensure prompt resolution of issues to give users a positive experience, it will generate a hard data on the frequency and ability to resolve specific problems in an intervention.

<u>Hardware</u>

Recognizing that cellular connectivity, power supply, complexity, and cost are the greatest shortcomings of the ST5, Nexleaf is developing two next generation devices to address these issues:

Bluetooth
This credit-card shaped device will fit easily onto the body of the stove, and uses a shortened version of the existing temperature probe. With a three year battery life, no power supply is needed. The device will store up to three months of data locally, during which time a staff member with the Nexleaf smartphone app must come within 15 feet of the device and download the data to his or her phone. From there, it will be automatically uploaded to the StoveTrace dashboard whenever the phone has an internet connection. This eliminates the need for cellular connectivity. If the device malfunctions, it is simply replaced and repaired by the manufacturer. It will cost less than $15USD.

Figure 26. Left: Bluetooth prototype with 10 rupee coin for scale. Right: Bluetooth prototype testing on a stove.

NFC
This flexible device will attach directly to the side of a stove using special heat resistant adhesive. Like the Bluetooth device, it also has a three year battery life and three months of local data storage. However, the staff member must place his or her phone on the device to download the data (which will then be transmitted via phone to the StoveTrace dashboard). It will cost less than $10USD.

Figure 27. Flexstr8 device on the Mimi Moto (left) and Greenway Jumbo Stove (right).

Carbon Monoxide (CO) Bangle

Monitoring CO exposure is a logical next step in fully understanding the health implications of domestic cooking. Although CO monitors were not tested as part of this project, in cooperation with Intel, Nexleaf has developed a prototype CO monitor housed inside a bangle bracelet which alerts the user if CO levels get too high. By placing the sensor inside an attractive piece of jewelry, users are much more likely to keep it on their body and collect reliable exposure data. Nexleaf coordinated a field pilot to test the first prototypes of the CO bangle in Uttar Pradesh with 10 pregnant women at least 18 years of age. Data was collected over a period of four weeks through in-person interviews. Participants who received the CO alerts reported improved awareness and behavior change. Participants liked that the bangle spoke to them, but reported that it was not water-resistant or aesthetically pleasing enough.

Figure 28. The CO bangle Nexleaf co-developed with Intel

Black Carbon Testing

In 2015, the Gold Standard Foundation, TERI, University of California at San Diego, the Global Alliance for Clean Cookstoves, and Nexleaf Analytics developed a methodology for the quantification and monitoring of black carbon (BC) emissions and other short lived climate pollutants.[7] “The particles emitted by biomass stoves consist mainly of black carbon (BC) and organic carbon (OC), and mix with particles from other sources to form ambient air pollution. Exposure to these particles indoors (mostly in homes) is responsible for 3.5 million deaths annually. There is an environmental impact as well. BC is a strong absorber of solar radiation and hence a climate warming agent.”[8]

Therefore, it is critical to include black carbon in the overall quantification of climate and health impacts pertaining to the switch from traditional to improved cooking. For climate impacts, reductions in BC can be converted to CO_2 equivalents (CO_2e) to facilitate aggregated summaries of climate impacts across a number of climate related pollutants.

Currently however, BC data from laboratory and field studies of improved cooking are scarcely available because the measurement equipment for continuous and laboratory sample evaluation is very expensive. Nexleaf has developed an inexpensive, smartphone-based method for measuring black carbon from filter based samples. This method has been favorably compared to far more expensive methods.[9]

As an independent evaluator, Indian Institute of Technology (IIT) Delhi has used this method to determine the BC emissions of nine different improved cookstove models in a laboratory setting. These results will be built into the StoveTrace dashboard, allowing it to calculate different CO_2e reductions based on the particular stove model in use. It also paves the way to pay different climate credit amounts to users based on the cleanliness of their stove. For example, if a user opts for a cleaner but less user friendly top loading forced draft stove over a dirtier but more familiar side-loading natural draft stove, she will be rewarded with larger climate credit payments.

[7] Gold Standard Foundation. *Pioneering Methodology for Tackling Black Carbon*. The Gold Standard Foundation, 31 Mar. 2015. Web.
[8] Ramanathan, T., Ramanathan, N., Mohanty, J., Rehman, I. H., Graham, E., & Ramanathan, V. (2016). Wireless sensors linked to climate financing for globally affordable clean cooking. *Nature Climate Change*.
[9] Ramanathan, N., Lukac, M., Ahmed, T., Kar, A., Praveen, P.S., Honles, T., Leong, I., Rehman, I.H., Schauer, J.J., Ramanathan, V. (2011). A cellphone based system for large-scale monitoring of black carbon. *Atmospheric environment* 45.26. 4481-4487.

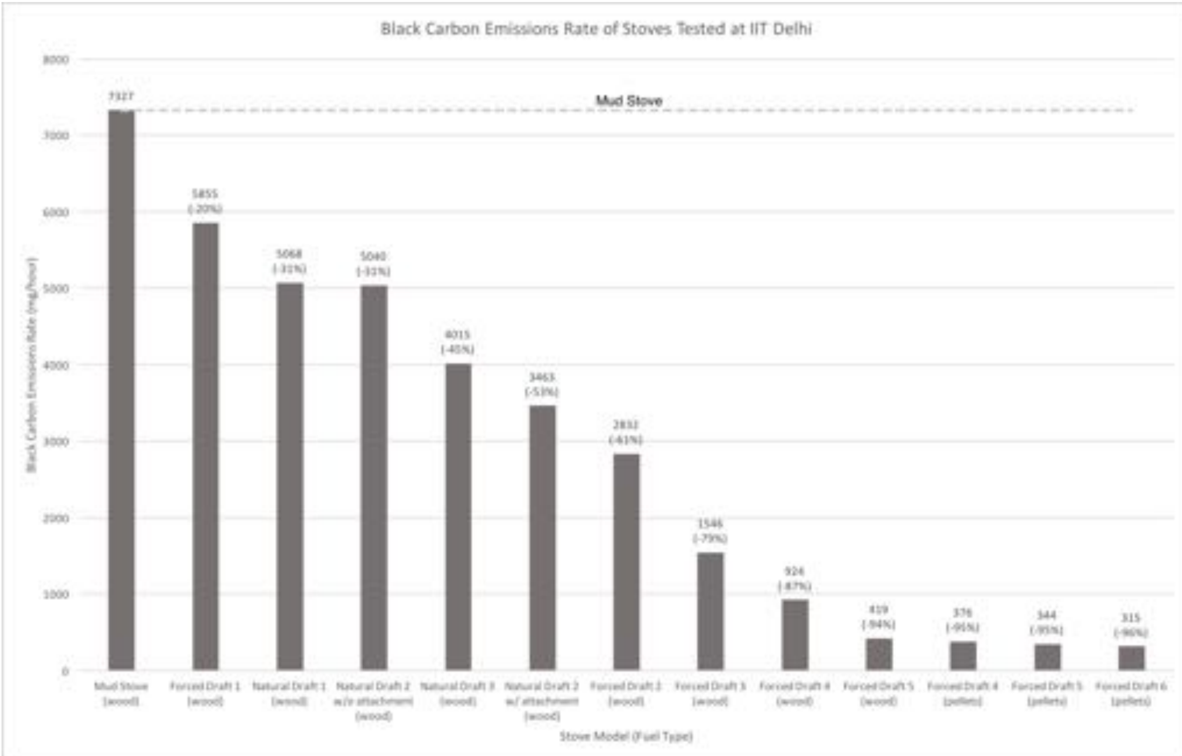


Figure 29. Black carbon emissions of the tested stoves, in ascending order of cleanliness from left to right. The value in parentheses indicates the percent reduction relative to a traditional mud stove in India. Note that two stove models (Forced Draft 4 and 5) were tested with both wood and pellets, and that one model (Natural Draft 1) was tested with and without a secondary “combustor” attachment.

The results reveal some interesting trends. As expected, even the dirtiest forced draft stove outperforms the cleanest natural draft stove – but not by much in the case of natural draft stove 2 with the special attachment that facilitates improved secondary combustion. Also as expected, the forced draft stoves reduce black carbon the most when using pellets as fuel – but only incrementally so. This introduces the exciting possibility that these stoves could still be used with chopped wood by users in regions where pellets are not available – but this would require further field testing to gauge real-world user feedback.

Among stoves with similar BC reductions (e.g. less than 1% difference between forced draft 4, 5, and 6) there are significant differences in cost, usability, and other performance metrics. This opens up the possibility to create a catalogue of a few stoves which provide users with a range of choice in terms of cost, usability, climate credit earnings, etc. so that they can find a stove that works for them. Meanwhile, by focusing on just a few stoves which cover this range of attributes, practical considerations like repairs and replacements can be kept manageable.

However, to truly anticipate potential climate and health impacts, field studies are needed to evaluate actual reductions in ambient concentrations of black carbon (and other toxic pollutants) to evaluate improved cooking technologies in real-world settings.

11. Conclusion and Next Steps

Key Next Steps:

- Develop and test method for stability of calibration of $PM_{2.5}$ sensors in long-term deployments
- Conduct field trials to evaluate the CO bangle for personal exposure measurements and integrate CO data stream on the dashboard
- Finish development of NFC and Bluetooth devices to achieve $10 cost target and enable scale
- Integrate thermal sensors inside 2-3 stove models to reduce cost and improve compatibility
- Test the entire updated hardware system and monitoring methodology in 500 households

Over the last year, StoveTrace sensors were deployed in 79 households in India, yielding unprecedented insight and spurring tremendous technological development of the platform. While some deployments saw minimal sensor issues and >95% adoption of the improved stove, others were hindered by breakdowns and complex stove stacking. Sensor data corroborated qualitative metadata, and user demand in Odisha for a large, side-loading stove was abundantly clear. Furthermore, the health benefits of cleaner air are less immediate and tangible, and do not hold much sway over the women's preference. Deployment of StoveTrace sensors at a larger scale, and in other geographies, could shed further light on user preference and behavior.

The StoveTrace dashboard was overhauled with an extensible architecture, more advanced analytics, and the ability to process $PM_{2.5}$ data, but further development to incorporate new data streams, more detailed analytics, and track sensor issues is needed. Nexleaf also envisions a "stove marketplace" whereby stoves can be independently tested, catalogued, and differentiated in terms of climate and health metrics on the dashboard.

An algorithm and protocol for converting raw $PM_{2.5}$ into approximate personal exposure levels was developed in conjunction with Berkeley Air. The outputted data can then be input to HAPIT to yield ADALYs. This is currently a manual process, and further work with the HAPIT team is needed to integrate the platforms so that ADALYs are automatically generated on the StoveTrace dashboard. If CO data streams are added to the dashboard, then work could also be undertaken to integrate CO sensors into the StoveTrace platform and devise a set of CO-related health metrics, which might include impact on newborns due to long-term low level prenatal CO exposure. Additional climate metrics could also be, for example taking snow melt and other impacts of SLCPs into account.

The ST5 proved to be a worthwhile evolution of the StoveTrace hardware, giving the first look at stove stacking and enabling the integration of $PM_{2.5}$ sensors. Yet it falls short in that it requires cellular signal (which is frequently unavailable in rural communities) and troubleshooting malfunctions is too complicated for most field staff. The development of a cheaper, simpler, and more robust hardware is perhaps currently the single most critical objective for StoveTrace. Development of two new non-cellular sensors is underway, but more resources must be focused on design, field testing, and cost reduction in order to make StoveTrace a truly scalable solution. **These devices have a price target of less than $10 to enable their placement on every stove to fully understand adoption.** Nexleaf will also work with 2-3 manufacturers to integrate the thermal probes inside the stoves to reduce costs and improve compatibility, setting the pathway for scale.

Of the three $PM_{2.5}$ sensors originally evaluated, two performed well enough to warrant integration with the StoveTrace platform. In lab tests, the PATS+ displayed superior performance against gravimetric averages, yet HAPEx also performed well. In field tests, the two devices performed nearly identically against gravimetric averages, however real-time analysis revealed interesting differences in sensor performance across different concentration ranges. While the PATS+ performed well at $PM_{2.5}$ concentrations above 500μg/m^3, it showed remarkably worse performance below that threshold. While there was not enough data to determine the HAPEx's performance above 500μg/m^3, it outperformed the PATS+ under 500μg/m^3. While this could indicate differing capabilities of the sensors at different concentrations, further study is needed to confirm.

On other attributes, the sensors receive mixed scores. The PATS+ is more than four times as expensive as the HAPEx, but also comes with more sophisticated software. The PATS+ software, called PICA, allows one to set any sampling interval, and perform some analysis of the data. The HAPEx software only allows sampling at certain intervals and can only export the data to be analyzed externally. Accordingly, the PICA software is fairly complicated to use, while the HAPEx interface is easy to operate. Lastly, the HAPEx has a far superior battery life of several years, compared to only 24-48 hours for the PATS+. If integrated with and receiving power from StoveTrace, this could be a non-issue.

With deployment of the integrated $PM_{2.5}$ devices in only 10 households, the results are extremely preliminary, yet on visual inspection they show a clear relationship between cooking events and indoor $PM_{2.5}$ levels, which is encouraging. The devices are very much prototypes, and much more development and field testing is necessary to turn them into proper products and draw meaningful conclusions about HAP from their data.

It would beneficial for Nexleaf to conduct a field trial with Tata Trusts to evaluate the end-to-end monitoring system in 500 households which are already part of an existing Tata Trusts deployment to showcase use of this open data platform and the monitoring methodology by an active clean cookstove implementer, refine processes to use the platform to understand and improve ICS adoption, and quantify the health and climate benefits.

Lab and field based evaluation of low cost $PM_{2.5}$ sensors

January, 2017

The Energy and Resources Institute

...towards global sustainable development

Summary

The augmentation of new technologies in environmental monitoring field creates enormous opportunities to generate comprehensive data sets which are required to assess the actual impacts especially on human health. One such field of research where human health is at stake is household/indoor air pollution. However, both outdoor and indoor monitoring of air pollutants is a cost intensive task considering the high-end cost of the devices and their maintenance. With an upsurge of monitoring based research studies on indoor air quality and human health assessment specifically in rural households of developing countries, it is imperative to shift focus towards development of low cost air monitoring devices that are reliable and affordable at the same time. Recently, development of low cost PM monitoring sensors has sparked an interest among researchers to employ such devices for assessing human exposure to the indoor air pollutants. However, these sensors need to be validated for their performance using the reference methods so that the data generated can be used to establish human health risks associated with indoor air pollution.

This report is an attempt to contribute to the existing research conducted on these low cost PM sensors. The study assessed performance of three low cost PM sensors based on some parameters that are crucial to define that these sensors are fit for future indoor air quality monitoring research where human health impact is an important output. Both lab and field based study designs were used to validate the sensor data with gravimetric method and an optical particle sensor (OPC) developed by GRIMM Technologies, Germany. The results of the study showed that these sensors correlate well with reference methods, however, based on certain usability parameters such as user friendliness of hardware and software components these sensors can be further upgraded.

1.0 Background and rationale

Increasing awareness about the adverse health impacts of solid biomass burning in traditional cookstoves, mostly in low and middle income countries, has led to a surge of technological interventions in the clean cooking sector. In order to combat this menace a lot of work is underway in developing clean cooking technologies which aim to reduce indoor pollution to healthy levels and comply with World Health Organization (WHO) standards for indoor air quality (IAQ). For the very purpose of assessing the impacts of such interventions on IAQ a wide range of indoor air monitoring instruments are available which approved by U.S. Environmental Protection Agency (EPA) for their efficacy. Indoor air pollution resulting from domestic cooking includes various pollutants such as carbon monoxide (CO), nitrous oxides (NOx), sulfur oxides (SOx), volatile organic compounds (VOCs), and particulate matter (PM). Among them all, $PM_{2.5}$ – particles with a diameter less than 2.5 micrometers - is considered the most significant contributor to death and disability (Mehta et al., 2013). The most accurate and trusted method for measuring PM is gravimetric sampling, a technique whereby filters attached to pumps physically collect airborne PM, and the before and after weights of the filter and total air sampled yield the average concentration of PM in the air during the sampling period (Baumann et al. 2006). Since human exposure to air pollutants is a function of time, space and activity (Otto, 1982) it is important to capture the large and rapid fluctuations of household PM levels which can occur during the sampling period. These fluctuations have significant health implications, but are not reflected in the average values given by gravimetric method (Steinle et al., 2013).This has led to the development of real-time PM monitors which work on different principles of optical light scattering, although they still require a small amount of gravimetric co-sampling for reference calibration. Historically these sensors have been prohibitively expensive with costs ranging between $9000 to $25000 (Budde et al. 2013), but recently a spate of low cost real-time PM monitors have been developed. They are gaining in popularity among researchers, as they provide considerable accuracy and precision, and at $100-500 each, are feasible for large-scale simultaneous monitoring of multiple locations. These monitors are equipped with sensors that work on light scattering principle similar to their costly predecessors, the difference being in the light source. The technology, however, is still in its nascent stage and must be validated with rigorous scientific investigations. These low cost sensors have been tried and tested for ambient monitoring of PM which is evident from the number of studies that are available in the literature (Holstius et al., 2014; Gao et al., 2015; Austin et al., 2015). Likewise, efforts have also been made to use these sensors to monitor indoor air quality and have been constantly upgraded in order to improve in terms of performance and usability parameters (Masera et al., 2007; Chowdhury et al., 2007, Armendariz-Arnez et al., 2010). The present study has been conducted to assess the three models of low cost $PM_{2.5}$ sensors designed specifically for IAQ monitoring for assessment cookstove performance in real world conditions. The study has attempted to develop protocols for assessing sensor performance both in laboratory and field settings, and to perform validation using reference methods of $PM_{2.5}$ measurements.

2.0 Objective of the study

To develop laboratory and field evaluation protocols for real-time $PM_{2.5}$ sensors, and apply this method to evaluate performance of three commercially available products. The larger objective is to create an integrated platform to translate the reduction in exposure to indoor air pollution into quantitative health benefits achieved by introduction of improved cookstoves in rural communities.

3.0 Co-location chamber

A cylindrical aluminum co-location chamber (with 17-inch height and 15-inch diameter) was used to test the sensors against gravimetric sampling system and GRIMM aerosol spectrometer. The chamber was fitted with a small mixing fan at the top which was run by a 9V battery. A vent connected to aluminum pipe at the base of the chamber was used to introduce and release the smoke.

A thin metal rod was fixed in the middle of the chamber where the sensors, GRIMM sampling tube and cyclone for gravimetric sampling could be stringed. Holes large enough to provide easy passage of silicon tubing and still narrow to avoid leakage of gases were made.

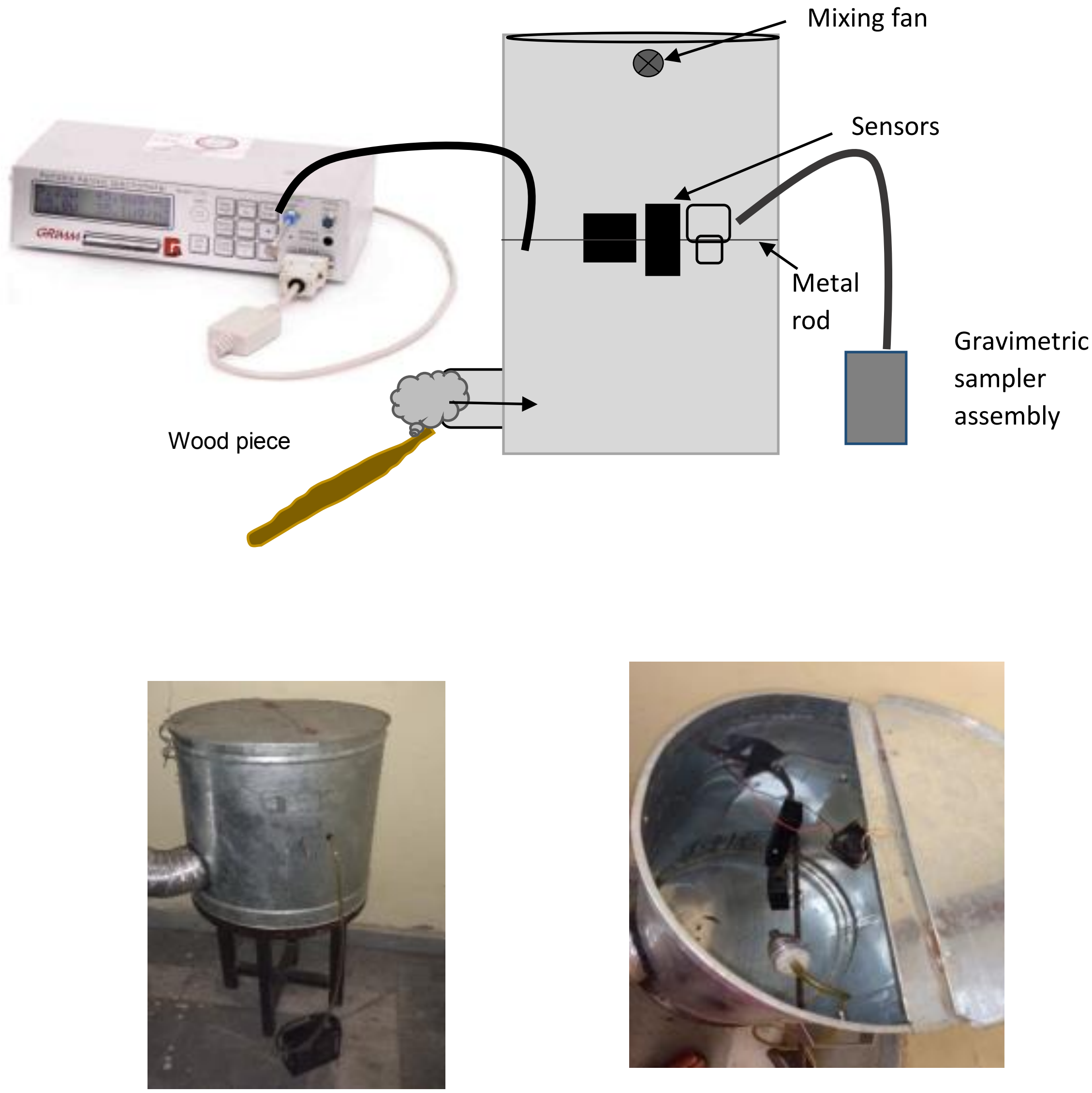


Figure 1 Schematic of the lab experimental set-up

3.0 Description of $PM_{2.5}$ sensors and validation methods

3.1 PATS+

PATS+ is a portable $PM_{2.5}$ sensing device developed by Berkeley Air Monitoring Group specifically for monitoring of indoor air pollution. It works on the principle of LED-based light scattering in an optical chamber.[1] The sensor module used in PATS+ is Sharp dust module which

[1]http://www.aqmd.gov/docs/default-source/aq-spec/resources-page/the-ucb-pats-monitor-a-short-history-with-list-of-publications-from-around-the-world.pdf?sfvrsn=0

has a light emitting diode, a detector, a lens and a slit oriented in way so that the detector captures the reflection of light and concentrations are derived from voltage output with the help of an amplifier circuit.[2] The PATS+ is commercially available for approximately $500.

3.2 HAPEx Nano

HAPEx Nano is also a portable sensor developed for monitoring $PM_{2.5}$ concentrations in the indoor air and for monitoring human exposure to $PM_{2.5}$. HAPEx uses the same sensor module as the PATS+. The HAPEx Nano is commercially available for $120.

3.3 Air Beam

The third sensor, well known as AirBeam, is available as a part of an open source platform which is combination of sensors meant for both environmental and physiological monitoring. Using the light scattering principle, the sensor measures $PM_{2.5}$ in real time and data can be accessed using an Android app called Aircast installed in a smart phone. The measured data from each sampling session is sent to the Aircasting website and is compared to the data shared by different users using Heat Maps. Air beam is also available commercially at a cost of ~$200.

3.4 Optical particle counter

The optical particle counter (OPC) used in the study is a device developed by GRIMM technologies, Germany. The device counts particles by counting the number of pulses of light scattered inside the measuring cell wherein light is sourced by a semiconductor laser (Peters et al., 2006). The instrument is used for size selective sampling in 15 different size channels with equivalent optical particle diameters ranging from 0.3 µm to >20 µm. It is calibrated yearly with NIST (National Institute of Standards and Technology) certified, traceable Poly-Styrene Latex. With a resolution of 1 count per liter of air and a reproducibility of ±2% it is one the most reliable instrument for real time PM monitoring. However, the cost the instrument is on the higher end touching around $25000 and above.

[2] http://www.sharp-world.com/products/device/lineup/data/pdf/datasheet/gp2y1010au_appl_e.pdf

3.5 Gravimetric sampling assembly

The gravimetric sampling assembly consists of a sampling pump, connecting tubes, polytetrafluoroethylene (PTFE) filter, filter cassette, and personal sampling cyclone with particle size cut point (D_{50}) 2.5 µm at 1.5 LPM. The principle involved in this method requires collection of particles with aerodynamic diameter less than the cut point of the inlet on the filter. The mass of these particles is then calculated by determining the difference in weight of the filter before and after the sampling. The difference in weight is used to calculate the concentration by dividing it by the total air sampled during the sampling time.

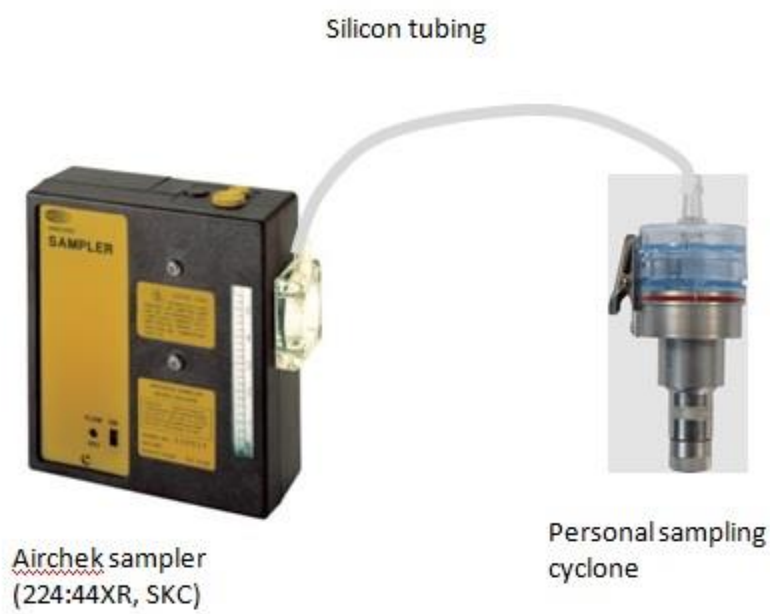


Figure 2 Assembly of gravimetric measurement system

4.0 Lab test protocol

4.1 Gravimetric

1. Mark all the filter cassettes to be used for gravimetric sampling with unique IDs in order to avoid interchanging of different samples.
2. Set the flow rate of the pump at 1.5 liters per minute and note down the exact initial flow rate using a flow meter.

3. Clean and dry the cyclone with cotton swabs.
4. Attach the tubing and filter cassette to the sampler.

4.2 Sensors and Aerosol spectrometer

Perform all the necessary steps to set the important parameters such zero air calibration (only for sensors), data logging rate, date/time etc. (Details are provided in the manuals provided by the respective manufacturers).

4.3 Placement of equipment inside the co-location chamber

a) Gravimetric

1. Place the gravimetric sampler near the co-location chamber and insert the tubing through the hole provided at the middle of the chamber.
2. Attach the cyclone to tubing and string it to the metal rod firmly. Strictly avoid any sharp bends in the tubing which might affect the actual flow rate.

b) Sensors

1. Set the sensors in data logging mode
2. String the sensors to the metal rod firmly in an upright position (as recommended by the manufacturer).
3. Make sure the sample inlets of both sensors are properly aligned at the same height and also that inlet is not obstructed with the string used for tying the sensors to the metal rod.

c) OPC

Silicon tubing attached to spectrometer's sample inlet of the spectrometer and other end was aligned on metal rod in alignment with sensors and cyclone.

4.4 Steps of the test protocol

a) Pre-sampling steps

1. Put the mixing fan on.
2. Put on the aerosol spectrometer by following the operating manuals provided by the manufacturer.

3. Take a piece of burning wood piece and blow it off.
4. Introduce the wood piece into the chamber through the vent provided at the base of the chamber. Make sure the wood piece gives off smoke excessively if you want to test at higher concentrations otherwise use less smoky wood for testing at lower concentrations.
5. Take out the wood piece and immediately cover the vent and open it again after 5 minutes and leave it open till the test ends.
3. Watch the real time concentrations displayed by the aerosol spectrometer. Put on the gravimetric sampler (after 15 minutes of smoke introduction in this case) at the desired level of maximum concentration and note the start time (this would be the start time for sensors and aerosol spectrometer as well).
4. Continue sampling for a period of 30 minutes.
5. At the end 30 minutes put off the gravimetric sampler, note the time and take the final flow rate.
6. Put off the aerosol spectrometer and remove the sensors from the chamber.
7. Open the lid of the chamber and flush out all the smoke to get ready for the next test.

b) **Post-sampling steps**

Gravimetric

Place detached filter cassettes wrapped in an aluminum foil and store them at a temperature of around ~4˚C until the filters are re-weighed.

Sensors and aerosol spectrometer

Follow the post sampling steps for zero air calibration and downloading of data as per operating manuals.

5.0 Field monitoring protocol

5.1Installation

a) Kitchen equipment should be installed 1.5 meters from the ground and 1 horizontal meter from the center of the stove. Attempt to avoid placing equipment next to doors, windows or other openings. Also make sure it is not in a place where the emissions plume will flow directly through the equipment. Check that it will not interfere with the participant's activities.

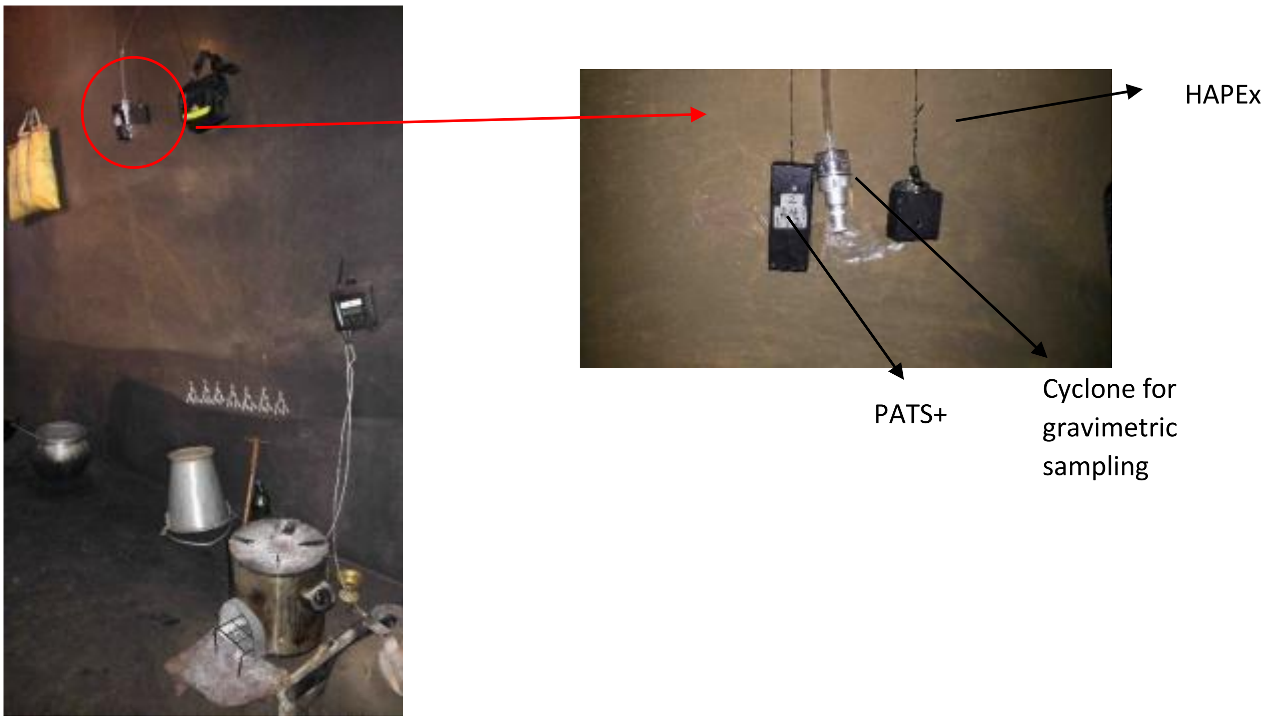


Figure3 Photograph representing co-located sensors and gravimetric sampling system in one of the HHs.

b) Gravimetric system

i) Select a filter cassette and connect the vacuum leak check pump to the inlet of the filter. Reject the filter cassettes with leakage.

ii) Note the filter ID on your survey form and write the household ID and the date on the label on the filter cassette, note ID of blank filter as well, if using.

iii) Calibrate the sampling pump

iv) Place pump in the cooler bag with the filter and cyclone hanging out of the cooler bag.

v) Turn the pump on when leaving the household and note this as the start time for the sample (for all instruments).

c) Write sample ID number on whiteboard or paper and take photographs that show detail of sampling equipment IDs and placement instrumentation. Take a close-up of the sampling equipment, and another photo that shows the sampling equipment and stove in the same shot.

2) Takedown

Gravimetric

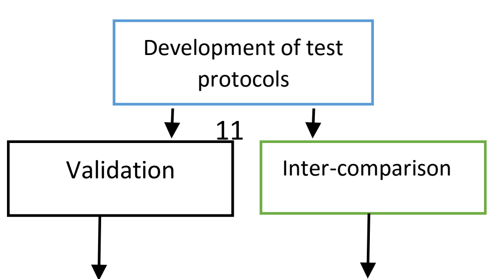
i) Stop the pump and record the stop time and total run duration.
ii) Take the final flow rate using the flowmeter and record it
iii) Unplug the tube from the cassette and replace the cab.
iv) Put on a pair of powder free gloves.
v) Use a coin to remove the cyclone, then quickly squeeze the cassette cap on
vi) Cover the cassette in tin foil, then place in a small plastic zip bag and seal.
vii) Place the bag inside the icebox and finally transfer it to freezer with temperature ~4˚C until re-weighed

Sensors

Record the stop time and remove all the sensors and download the data.

6.0 Study design

The study design represents two primary objectives of the study which includes validation of $PM_{2.5}$ data using reference methods and inter-comparison of other sensor performance parameters. Both lab and field studies have been designed to achieve the set objectives using the test protocols developed during the study.



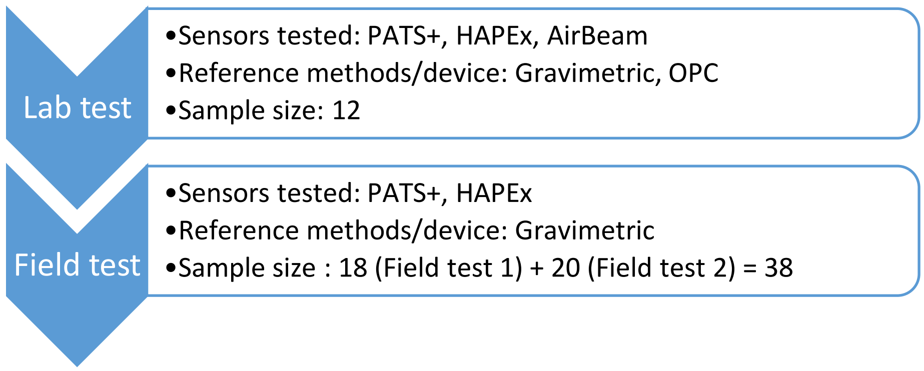


Figure 4 Study design

7.0 Methodology

7.1 Lab and field tests

The lab tests were conducted using the protocol described in section 4.0. A total of 12 experiments were performed at different average $PM_{2.5}$ concentration levels. The $PM_{2.5}$ measurements were validated with the measurements taken by a gravimetric sampling set-up as described in the protocol alongside an OPC.The field tests were conducted according to the protocol described in section 5.0. Tests were conducted during the months of March -June 2016 which come under summer season in the study region. It was important to limit the study to one season so that the metrological conditions were constant and had minimal effect on $PM_{2.5}$ concentrations over the entire study period. The field tests were also conducted with a primary to aim validate the sensor performance using 18-22 hourly, 7-8 hourly and 2-4 hourly average $PM_{2.5}$ concentrations in order to compare sensors at different concentration ranges. While longer duration samples yield the most accurate daily averages for converting to personal exposure, shorter durations which encompass cooking events give the highest PM2.5 values, necessary to test the upper detection limits of the sensors.The sensors were also compared based on certain parameters that included applicability, ease of operation (hardware and software), durability, and cost.

Figure 4 Validation of senor performance

7.2 Household selection for field evaluation

The field evaluation of sensors was conducted in Notarpalli village of Nayagarh, a district of Odisha. The study area is marked by considerable forest cover (15%)[3]making wood as the primary fuel available for cooking. 10 households (HHs) in the village were selected who gave consent to participate in the study and were provided with improved biomass cookstoves a month prior to the commencement of field evaluation of sensors. The kitchens of the households were characterized in terms of location and type. Out of 10 HHs six had an enclosed kitchen which can be described as a room surrounded by four walls and covered with a roof. The remaining four HHs had a semi-enclosed kitchen which was partially covered by mud walls with or without a roof.

8.0 Data analysis

Linear regression analysis was used to examine the relationship between the average $PM_{2.5}$ concentrations measured by the each of the two sensors and gravimetric sampling technique based on the R^2 values and RMSE (root mean square standard error) to check the accuracy of the estimated associations (Holstius et al., 2014). Real time $PM_{2.5}$concentrations measured by the sensors were also compared to OPC readings to assess the response to the instantaneous change in $PM_{2.5}$ concentrations over the sampling time. The association between the two was established using linear regression analysis.

9.0 Results

[3]http://nayagarh.nic.in/annualplan/Nayagarh%20Annual%20Plan%202010-11.pdf

9.1 Lab test

a) Validation of sensor data using gravimetric measurements

Data from a total of 12 lab tests was used to perform the linear regression analysis. However, in the case of HAPEx only 8 data points were available due to loss of data during sampling. The loss of data was due to a manufacturing defect in the sensor wherein the concentrations were not recorded by the device during sampling and were displayed as 0's. AirBeam, owing to its low upper concentration detection limit (400 µg m^{-3}) and no provision to access the raw data, was screened out at the beginning of the lab tests.

The R^2 computed for the regression analysis carried out for both the sensors indicated a strong positive association between the average $PM_{2.5}$ concentrations measured by sensors and gravimetric sampling. However, between the two sensors, PATS+ data was better correlated with the gravimetric data with a R^2 of 0.97 compared to 0.80 in case of HAPEx. There is a dearth of data on sensor performance evaluation, especially validation using gravimetric methods. A study conducted by Pokhrel et al. (2013) which assessed the earlier version of PATS+ called as UCB-PATS reported a R^2 value of 0.84.

Additionally, PATS+ data showed a lower normalized RMSE of 6% compared to 14% in case of HAPEx indicating higher accuracy of the regression model.

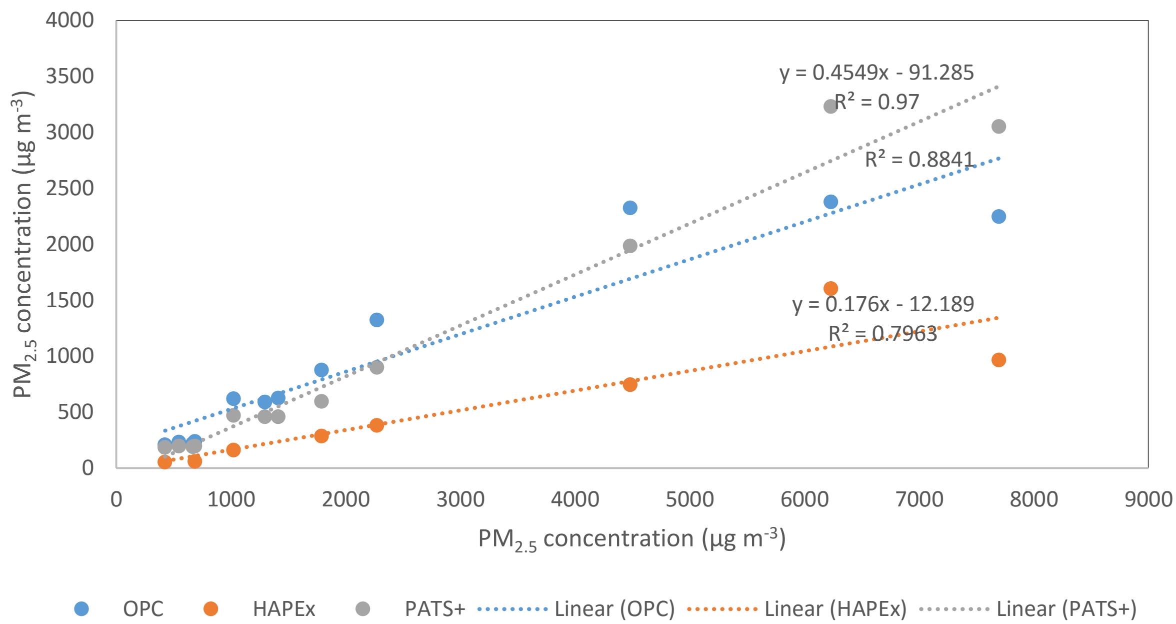


Figure 5 Linear regression analysis plot for lab based validation of average $PM_{2.5}$ concentrations measured by sensors with gravimetric and OPC $PM_{2.5}$ concentration measurements

b) Linearity of sensor $PM_{2.5}$ concentrations withOPC

When plotted against the real time GRIMM data, both sensors, PATS+ and HAPEx, demonstrateda strong linear relationship. However, the value of R^2 varied from 0.76 – 0.99 with an average of 0.91 in PATS+ data while in case of HAPEx the range was 0.39 – 0.98 with an average of 0.81 Figure 5 is an example of linear relationship established in one the tests. The GP2Y sensor module which has been used both in PATS+ and HAPEx has been previously tested in some studies. In a study conducted by Wang et al. (2015) the GP2Y sensor module correlated well withreference device (SidePak, TSI Inc., St. Paul, MN, USA) and the R^2 was found to be 0.98 which is in good agreementwith results of the present study. In another study conducted by Sousan et al. (2016) this sensor module was tested in lab with different types of aerosols and R2 ranged from 0.91 - 0.99 whichevidently proves the credibility of these low cost sensors.

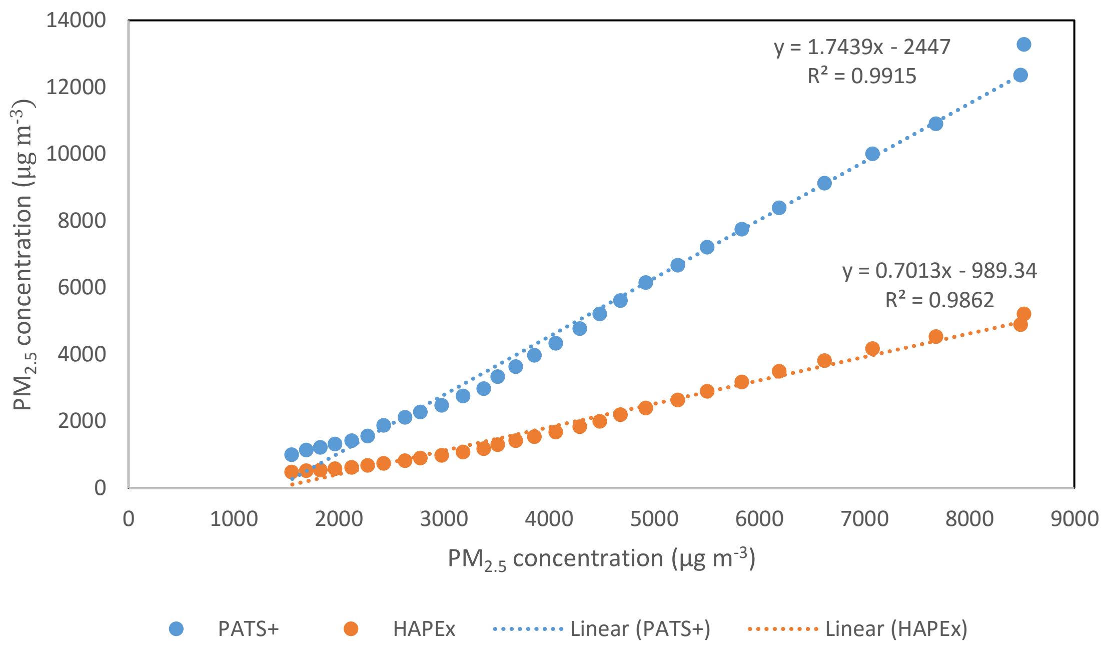


Figure 6 Linear regression analysis plot for lab based validation of real time $PM_{2.5}$ concentrations measured by sensors and OPC

9.2 Field test

Validation of sensor data using gravimetric measurements

The linear regression analysis was performed for 38 samples representing average $PM_{2.5}$ concentrations measured by co-locating sensors and gravimetric sampling system in each of the HH as described in the field test protocol. Out of the 38 gravimetric samples, the first five samples collected on Teflon filters were weighed in different laboratories which were likely to impact the calculated $PM_{2.5}$ concentrations. Therefore a correction factor was derived with the help of regression analysis wherein an equation between concentrations from types of filters was computed by co-locating five filters from each set. The slope of the regression equation was multiplied to the concentrations for 14 samples comparable to the rest of the lot. Unlike the lab tests, when the data from sensors and corresponding gravimetric values of $PM_{2.5}$ concentrations were regressed, the R^2 was found to be higher for HAPEx (0.75) compared to PATS+ (0.74). However, the normalized RMSE (11%) for PATS+ was still lower than HAPEx (18%) as in case of lab tests indicating that higher accuracy of regression model was demonstrated by PATS+.

The sensor response at different range of concentrations was also assessed through regression analysis. In case of PATS+ the R^2 (0.82) for $PM_{2.5}$ concentrations higher than 500 µg m-3 was found to be higher when compared to concentrations ranging between >30 and <500 µg m-3 for which the R^2 was 0.16. While HAPEx showed a stronger relationship (R^2 = 0.63) even at concentrations below 500 µg m-3.

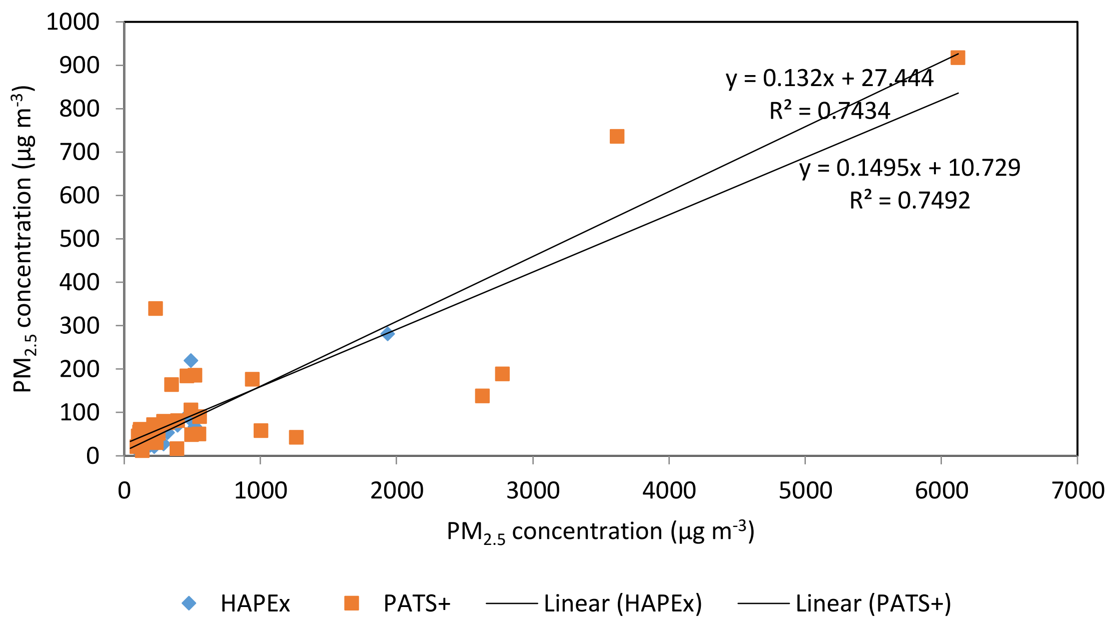


Figure 7 Linear regression analysis plot for field based validation of average PM2.5 concentrations measured by sensors with gravimetricPM2.5 concentration measurements

However, due to loss of data owing to some technical issues which have been already discussed in section 8.1.1 the R^2 for HAPEx data at higher concentration range could not be computed. The assessment of accuracy of the regression models showed PATS+ with 15% normalized RMSE for concentrations above 500 µg m-3 which was considerably lower than the normalized RMSE (25%) when the concentration was in the range of 31-500 µg m^{-3}. At higher concentrations i.e. above 500 µg m^{-3} and below ~6000 µg m^{-3} the RMSE for PATS+ (25%) again lower than HAPEx which was ~33%. The peak concentrations during cooking have been reported by Park and Lee (2003) to reach level of ~ 8000 µg m^{-3} which is a bit higher to the concentration observed in this study.

Table 2 Statistical summary of regression analysis and uncertainties

	R^2	Linear Correction Equation	RMSE	Normalized RMSE	# Samples	Concentration range during sampling (µg m $^{-3}$)
Lab test						
PATS+	0.97	y = 0.4549x - 91.285	186	6%	12	426 - 6232
HAPEx	0.80	y = 0.176x - 12.189	212	14%	8	
Field test						
PATS+	0.74	y = 0.1302x + 33.381	97	11%	33	95 – 6124
HAPEx	0.75	y = 0.2236x + 5.1129	67	25%	18	

9.3 Comparison based on other performance parameters

Table 3 provides a subjective measure of sensor performance based on other parameters such as cost, usability of software and hardware, battery life and overall applicability.

Cost: On the basis of per unit cost of sensor based PM monitoring devices, HAPEx has an edge over PATS+ as it can be procured at a price which is four times less.

Usability: The user friendliness and reliability of the device is of critical importance in order to maintain its performance standards. Both hardware and software should provide enough options which cater to the wide range of applicability defined by different users. Considering the diverse user requirements, between the two sensors evaluated in the study, PATS+ provides the user with varied options to customize the data collection process. The setting of data logging interval is an important element of monitoring which varies with aim of the study and is a crucial factor that cannot be overlooked. Although, HAPEx is equipped with software to allow user to set wide range of logging intervals, however, the in-built data logging rates do not match to most of the reference PM monitors thereby making calibration of the sensor a tedious task. Secondly, HAPEx needs to be connected to the laptop in order to give commands for initiating sampling which makes it cumbersome task if the monitoring is a part of a field based assessment.

The low weight, longest battery run time and wider detection range in HAPEx expands its applicability and therefore it can be used for both indoors and personal exposure monitoring without any interruption. PATS+ lags behind in these aspects especially because of the short span of battery run time.

Table 3 Technical and physical specifications of devices used in the study

Device	Sensor module	Principle	Max /Min detection concentration	Size and weight	Battery run time	Operating conditions	Logging interval	Storage temperature	Applicability
PATS+	Sharp GP2Y1010AU0F	LED-based light-scattering	10 - 50 mg m^{-3}	12.6 x2.6x 2.6 cm 0.11 kg	~36 hours	0 to 50° C	2 sec to 1 hour	4 to 38° C	Indoors and personal
HAPEx	Sharp GP2Y1010AU0F	LED-based light-scattering	8 - 150 mg m^{-3}	5×7.5×2 cm 0.065 kg	5 years	-	20 sec to 2.75 hours	-	Indoors and personal
AirBeam	Shinyei PPD60PV	LED-based light-scattering	Max 0.400 mg m^{-3}	10.5× 9.5× 4.3 cm 0.198 kg	~10 hours	-	-	-	Indoors and personal
GRIMM Aerosol spectrometer (1.108)	NA	Laser based light scattering	0.1 – 100 mg m^{-3}	24 ×13× 7 cm 1.7 kg	~8 hours	0 to 40° C	6 sec to 1 hour	-20° C to 50° C	Indoors and outdoor (with appropriate accessories)

10.0 Conclusion

Data collection techniques in exposure based health assessment studies are a crucial starting point. In this context, it is important to maintain the both quality and comprehensiveness of data generated. It is realized through this study that low cost sensors can be considered as a reliable alternative to expensive PM monitoring devices. However, these sensors still need to be validated at fixed intervals of time in order keep track of their consistency in performance. Short term performance assessment helps to understand the level of accuracy which can be achieved with these sensors and also the usability factors which play a critical role for applications where long term monitoring is required.

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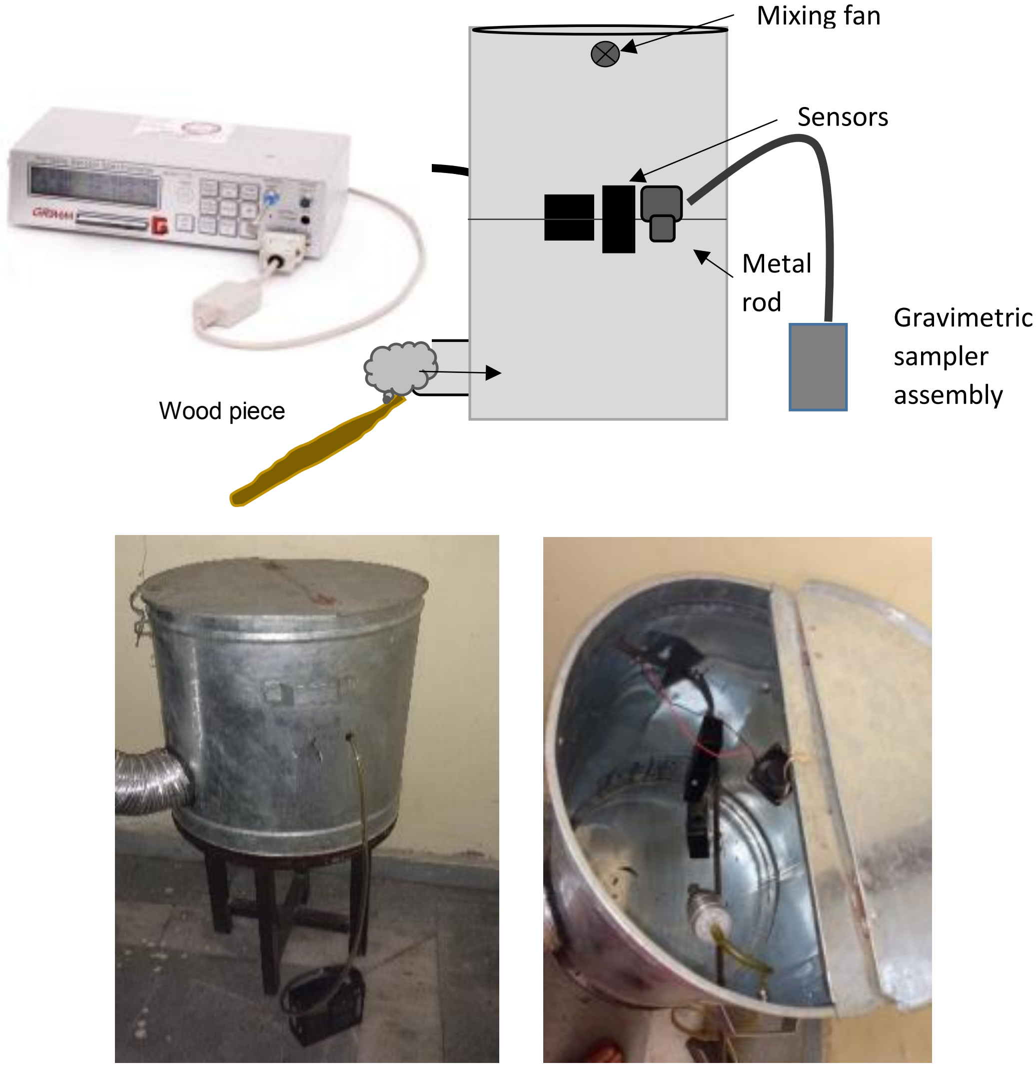
Protocol for evaluation of low cost $PM_{2.5}$ sensors in controlled lab setup

Experimental set-up

Co-location chamber

An aluminum co-location chamber (with 17-inch height and 15-inch diameter) was used to test the sensors against gravimetric sampling system and GRIMM aerosol spectrometer. The chamber was fitted with a small mixing fan at the top which was run by a 9V battery. A vent connected to aluminum pipe at the at the base of the chamber was used to introduce and release the smoke.



Schematic of the co-location chamber

Instrumentation

Principle of optical particle counters (OPCs) for size selective PM measurement

The OPCs used for PM sampling work on the principle of light scattering by single particle inside a measuring cell where light is sourced by a semiconductor laser. The scattered light pulse is received on a mirror angled to focus the light towards a detector. Eventually, the particles are counted and sized by 90° scattering light detection (Peters et al., 2006). The instrument is used for size selective sampling in 15 different size channels with equivalent optical particle diameters ranging from 0.3 μm to >20 μm. The instrument reports aerosol particles as number per liter of the air sampled.
The instrument is calibrated yearly with NIST (National Institute of Standards and Technology) certified, traceable Poly-Styrene Latex.

Gravimetric sampling assembly

The gravimetric sampling assembly consists of a sampling pump, connecting tubes, PTFE filter, filter cassette and personal sampling cyclone with particle size cut point (D_{50}) 2.5 μm at 1.5 LPM.

Airchek sampler
(224:44XR, SKC)

Personal sampling
cyclone

Test protocol

Preparatory steps

Gravimetric

1. Mark all the filter cassettes to be used for gravimetric sampling with unique IDs in order to avoid interchanging of different samples.
2. Set the flow rate of the pump at 1.5 lpm and note down the exact initial flow rate using a flow meter.
3. Clean and dry the cyclone with cotton swabs.
4. Attach the tubings and filter cassette to the sampler.

Sensors and Aerosol spectrometer

Perform all the necessary steps to set the important parameters such zero air calibration (only for sensors), data logging rate, date/time etc. (Details are provided in the manuals provided by the respective manufacturers).

Placement of equipment inside the co-location chamber

Gravimetric

1. Place the gravimetric sampler near the co-location chamber and insert the tubing through the hole provided at the middle of the chamber.
2. Attach the cyclone to tubing and string it to the metal rod firmly. Strictly avoid any sharp bends in the tubing which might affect the actual flow rate.

Sensors

1. Set the sensors in data logging mode
2. String the sensors to the metal rod firmly in an upright position (as recommended by the manufacturer).
3. Make sure the sample inlets of both sensors are properly aligned at the same height and also that inlet is not obstructed with the string used for tying the sensors to the metal rod.

Aerosol spectrometer

Silicon tubing attached to spectrometer's sample inlet of the spectrometer and other end was aligned on metal rod in alignment with sensors and cyclone.

Test

1. Put the mixing fan on.
2. Put on the aerosol spectrometer by following the operating manuals provided by the manufacturer.
3. Take a piece of burning wood piece and blow it off.
4. Introduce the wood piece into the chamber through the vent provided at the base of the chamber. Make sure the wood piece gives off smoke excessively if you want to test at higher concentrations otherwise use less smoky wood for testing at lower concentrations.
5. Take out the wood piece and immediately cover the vent and open it again after 5 minutes and leave it open till the test ends.
3. Watch the real time concentrations displayed by the aerosol spectrometer. Put on the gravimetric sampler (after 15 minutes of smoke introduction in this case) at the desired level of maximum concentration and note the start time (this would be the start time for sensors and aerosol spectrometer as well).
4. Continue sampling for a period of 30 minutes.
5. At the end 30 minutes put off the gravimetric sampler, note the time and take the final flow rate.
6. Put off the aerosol spectrometer and remove the sensors from the chamber.
7. Open the lid of the chamber and flush out all the smoke to get ready for the next test.

Post-sampling steps

Gravimetric

Place detached filter cassettes wrapped in an aluminum foil and store them at a temperature of around ~4˚C until the filters are re-weighed.

Sensors and aerosol spectrometer

Follow the post sampling steps for zero air calibration and downloading of data as per operating manuals.

Monitoring Cookstoves for Impact and Behavior Change

Delhi - March 14, 2016

Purpose

To bring together key entities with significant investment in the cookstove sector to develop a common framework for monitoring, data collection and reporting.

Background

Improved cookstoves can significantly reduce air pollution inside homes, save millions of lives, and reduce the amount of global warming pollutants emitted into the atmosphere. However, the positive environmental and health impacts that improved cookstoves are supposed to deliver can vary dramatically based on a number of factors, including the stove technology selected, the actual usage of the stove, the fuel consumed, and the context of use.

The most impactful technologies and interventions must be identified, financed and scaled up in order to maximize the climate and health benefits of improved cookstoves. More data is needed to determine the most efficient, effective and usable stove technologies and to understand which implementation models and stove types are most appropriate for various potentials users.

In order to identify the best technologies, the following problems must be addressed:

1) There is no timely way to identify which stove distribution interventions are succeeding, nor which ones are resulting in low adoption or quick breakage in the field.
2) There is no platform for sharing data among cookstove stakeholders that would enable various interested groups to compare interventions across multiple dimensions (such as demographics, geography, stove design).
3) There is no low-cost method for large-scale and timely collection of the data needed to calculate the climate and health impacts of improved cookstoves in the field.

The time to act is NOW

- The Cop 21 Paris Agreement Committed **$100 Billion** a Year to Climate Financing.
- Breakthrough Energy Coalition Committed **$1 billion** for clean energy innovation.

Workshop Objectives	Deliverable/Outcome
A) Identify opportunities, challenges & solutions in monitoring.	Enumerate the use cases of monitoring from a diverse set of stakeholders.
B) Determine what to measure and how.	Informal guidelines for a uniform monitoring methodology & metrics for success.
C) Strategy for leveraging existing monitoring programs.	Gather feedback on an open access dashboard.
D) Discuss guidelines & roadblocks for anonymizing data and keeping it public.	Finalize a data sharing agreement and a framework for data collection and reporting

The World Bank

NEXLEAF ANALYTICS

List of organizations in attendance at the March 14th, Delhi Workshop

3eSavers
Aakar Energy Ventures
Ashden India Renewable Energy Collective (AIREC)
Community Lead Environmental Action Network (CLEAN)
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
Dharma Life
Envirofit
Global Alliance for Clean Cookstoves (GACC)
Greenway Appliances
International Finance Corporation
Ministry of New and Renewable Energy (MNRE)
Navdurga Metal Industries (NDMI)
Nexleaf Analytics
Okapi
Prakti Design
Qualcomm
Self Employed Women's Associated (SEWA)
Tata Trusts
The Energy and Resources Institute (TERI)
World Bank

MONITORING FOR IMPACT and BEHAVIOR CHANGE

A Cookstove Monitoring Framework for Climate Impacts, Health Impacts, and Behavior Change

**Note to all experts: This document attempts to capture and summarize what has been discussed thus far in the working group. All terms, definitions and protocols are recommended, and open to discussion. It is our hope that this document, by starting simply, encourages participation, editing, and comment.*

I. OVERVIEW

Improved cookstoves can significantly reduce air pollution inside homes, improve millions of lives, and reduce the amount of global warming pollutants emitted into the atmosphere. However, the positive environmental and health impacts that improved cookstoves are supposed to deliver can vary dramatically based on a number of factors, including the stove technology selected, the actual usage of the stove, the fuel consumed, and the context of use. *The most impactful technologies and interventions must be identified, financed and scaled up in order to maximize the climate and health benefits of improved cookstoves.* More data is needed to determine the most efficient, effective and usable stove technologies and to understand which implementation models and stove types are most appropriate for various potentials users.

A. Scope

This document aims to establish a set of guidelines that can be utilized to generate consistent, high quality, and comparable datasets. This document assumes the existence and utilization of the following data collection and analysis methods:

1. Continuous stove monitors (CSM): This refers to a subset of continuous monitoring devices that have a temperature sensor and can monitor stove adoption over time (e.g. SUMS or the ibutton, StoveTrace and SweetSense). (*Terminology adopted from the Gold Standard Foundation's methodology.)*
2. Continuous monitors (CM): Any electronic device that produces a time series for any measurement such as continuous PM 2.5 monitoring (e.g. PATS).
3. Open Data Platform: A centralized website for anyone to view time series data from CSM and/or CM.

As a working group, we aim to build ongoing monitoring into implementations and interventions. Ongoing monitoring, as opposed to one-time monitoring, begins at the onset of a stove intervention and continues on a regular basis as a means to enable rapid iterations to an intervention until the desired outcomes are met and verified.

B. Alignment

There are a number of ongoing and aligned initiatives that this effort will be leveraging and collaborating closely with:

1. ISO 285: International Standards Organization standard for field testing of cookstoves and cooking systems. Work in progress as of the writing of this document.
2. Gold Standard Foundation methodologies:
    a. Black Carbon methodology (published): Developed in partnership with Nexleaf Analytics, UC San Diego, Berkeley Air, TERI and others. http://www.goldstandard.org/blog-item/pioneering-methodology-tackling-black-carbon
    b. ADALYs (in progress): Averted Disability Adjusted Life Year. Aiming to develop a methodology to finance health and climate SDG (Sustainable Development Goals) impacts http://www.goldstandard.org/tags/adalys
3. HAPIT (Household Air Pollution Intervention Tool) http://www.worldbank.org/content/dam/Worldbank/document/HDN/Health/021214CQCandLaosStovesNewcombe.pdf
4. Ashden India Renewable Energy Collective (AIREC) Cooking Energy Service Decision Support Tool (funded by GIZ) http://thecleannetwork.org/downloads/79-AIREC-Tool---Manual---Nov-2015.pdf
5. Dharma Life consumer acceptance trial questionnaire – In progress

C. Objectives

To bring together key entities in the cookstove sector including stove manufacturers, distributors, researchers, governments, and donors to develop a common and open framework for ongoing monitoring, data collection, and reporting in order to support results-based financing for large-scale cookstove implementations by making it possible to:

1) Identify which stove designs and distribution interventions are succeeding, or which ones are resulting in low adoption or quick breakage in the field.
2) Provide an open data platform for sharing data among cookstove stakeholders that makes it possible to compare interventions across multiple dimensions (such as demographics, geography, stove design).

3) Provide a low-cost method for large-scale and timely collection of the data needed to calculate the climate and health impacts of improved cookstoves in the field.

II. METRICS

This effort aims to quantify impacts in terms of adoption, ADALY's, and climate impacts. The platform will be designed to be modular and extensible, so as methodologies improve to define the following metrics, and as CSM become more cost-effective and available, the platform can be updated.

ADALY: Averted Disability-Adjusted Life Years (ADALY's) are a mechanism for quantifying the burden of disease and early death which is avoided through a given intervention. The amelioration of respiratory and other illnesses through the use of clean cookstoves can therefore be quantified in the form of ADALY's. ADALY's are calculated using an individual's personal exposure to harmful pollutants. The strongest and most clearly measureable link between stove usage and illness is exposure to $PM_{2.5}$ - particulate matter with a diameter of 2.5 micrometers or less. A robust and replicable protocol for connecting stove usage to $PM_{2.5}$ exposure is currently under development by the Gold Standard Foundation, and will be incorporated into the results-based financing portion of this methodology.

Climate Impacts: Will begin by quantifying emissions reductions of CO_2 and black carbon (collectively expressed as CO_2 equivalents, or *CO_2e*), based on the Surya methodology, which was adapted by the Gold Standard Foundation and will be improved over time. Emissions estimated based on laboratory results and in-field measurements of cookstove usage.

Adoption: Can be defined in terms of the total daily cooking duration (hours), frequency of usage over time, and displacement of traditional cooking. Ubiquitous stove monitoring can show the variability of stove usage to be expected among the target population, both across the population and over time. Further, for example, a particular household's stove usage could qualify them to receive a commensurate ADALY payment (e.g. 95% stove utilization could qualify them for 95% of the full ADALY value).

Exposure: The top of the platform represents the most expensive and logistically difficult to collect (e.g. personal exposure), but the most direct (and therefore valuable) in terms of estimating ADALY's. Meanwhile, household air pollution (HAP) measurements are more affordable and less invasive, so they can serve as an intermediary, while stove usage may be the most affordable and least invasive, and can be deployed at the largest scale. Personal Exposure Monitoring (PEM) is meant to give a detailed look at individual short-term exposure and indoor air quality in a specified area.

HAP can establish the difference in household $PM_{2.5}$ concentrations between improved stoves and traditional stoves. Showing a difference in HAP is **required** in order to establish the source of ADALYs as being from the improved cookstove. Therefore, HAP monitoring can be repeated every year to account for any changes in stove emissions over time and allow for annually revised ADALY's based on stove usage and performance.

> **A strong link between HAP and exposure is yet to be shown, therefore some number of households will likely require exposure monitoring.** This is an area of ongoing development.

III. PROTOCOLS

Monitoring parameters (e.g. sample size, sampling duration, etc.) will vary depending on a number of factors including the objectives, size of expected outcome, and variability. *This document intends to provide guidelines for rapid start-up and iteration. Statisticians are required to calculate sample sizes for studies submitted for peer-review*.

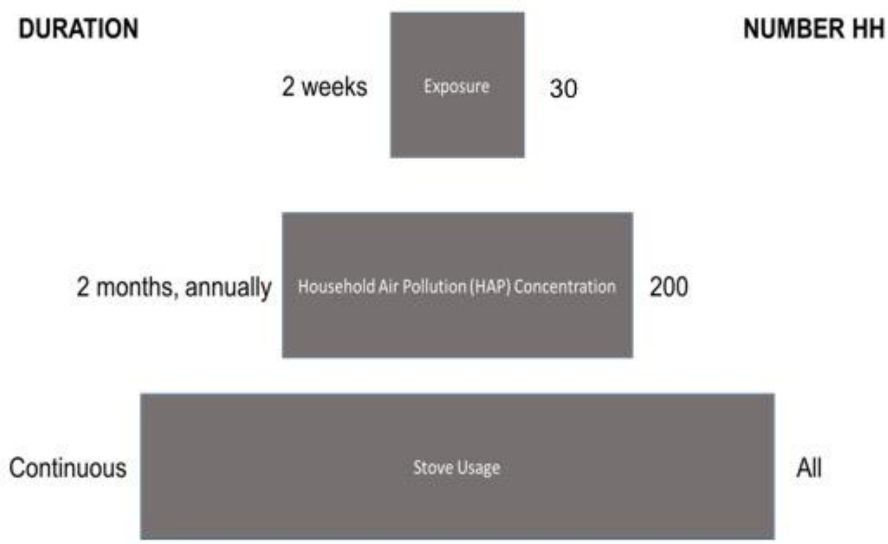
SAMPLE SIZE: We recommend the rule of thumb provided in KPT Version 3.0:[1] that: a) For groups of 300 households or less (per comparison group) the sample size should be at least 30 households per group, b) For medium sized groups (300-1000 households) 10% of households should be selected, and c) for large groups (>1000 households), at least 100 households should be selected. All samples should be randomized.

Monitoring for climate impacts requires monitoring emissions of black carbon, organic carbon and other climate sensitive emissions directly from the stove; however emissions monitoring is expensive and intrusive. Similarly, monitoring for ADALY's requires personal $PM_{2.5}$ exposure measurements, which are expensive, and intrusive for study subjects. Over time, in-field monitoring technologies will certainly improve and direct measurements will be feasible at large scale for these parameters.

We propose a tiered monitoring strategy (see below for an example), wherein links are developed between each tier of the platform. Using the sample below, 30 households would receive exposure monitoring, HAP monitoring, and stove usage monitoring. While 200

[1] Kitchen Performance Test (KPT) Version 3.0 – Prepared by Rob Bailis with input from Kirk R. Smith and Rufus Edwards. *Household Energy and Health Programme*. Shell Foundation (January, 2007)

households would receive HAP and stove usage monitoring (170 of these households would only receive these two, with 30 of these households also receiving exposure monitoring). This is simply an illustrative example.



The number of households, duration, and other parameters indicated in the tiered model would need to be determined based on the objectives and population sizes.

The following 3 thematic areas have emerged, and we include an example for each.

A. **Thematic Area 1: Data to improve Stove designs**
    a. Inform product design during the design phase (Real-time data)
    b. Inform immediate uptake during product launch (Weekly updates)
    c. Usage after purchase (Monthly updates)

CSM can be used to achieve all of the objectives above with a focus on validating customer preferences with concrete data. High usage rates indicate strong customer preference, whereas low usage rates reveal a flawed design. When paired with follow-up surveys, issues can be revealed and corrected. PM2.5 could be monitored in a subset of households to evaluate impact of stove on room area concentrations during the design phase (a).

Follow-Up/Future Objectives: Define technical probe placement in stove design, integration into stove manufacturing.

Example: In one community, tier 3 forced draft stoves were deployed in 900 households, tier 2 natural draft stoves were deployed in 900 households, and traditional stoves were utilized in 900 households. Households were selected in both the intervention and control groups, and both the intervention and traditional stoves were equipped with CSM. The real-time sensor data revealed that usage rates were vastly higher for the natural draft stove, despite being less clean. Weekly sensor data showing this pattern continuing triggered targeted in person follow-up surveys, and users expressed preference for the natural draft stove because it could accommodate larger pots to feed more people. Additionally, the forced draft stove released too many ashes onto the kitchen floor during cooking. Consequently, using the monthly sensor data as the evidence base, the manufacturer of the forced draft stove was informed that customers were demanding the natural draft stove, and they should consider designing their stove to accommodate larger pots.

- Sample size: minimum 90 households per group (one group using traditional stoves, one group using tier-3 stoves, and one group using tier-2 stoves) with CSM, with targeted follow-up visits, focus groups, and surveys with 50% of the households monitored with CSM.
- Frequency and duration of monitoring: One year. CSM recording every 10 minutes for entire intervention. Focus groups held at 1, 6, and 12 months. Individual surveys and stove inspections held weekly in the first month, then with each subsequent focus group. Recommend the approximately 6 month interval for in-person follow up so that **there is time to improve on the model or technology between follow up visits**. The key is to allow time for **iteration**.

B. Thematic Area 2: Data to improve Marketing, Distribution, Training, Post-Sales Service

a. Subsidization: Did user buy or get loan for stove (Monthly updates)

b. Behaviors: Types of meals cooked (Monthly updates)

c. Usage: Hours per day, can be used to predict payments, provide usage-linked payments, or re-inforce payment by ‘turning off stove’.

d. Breakage: Trigger service request

At scale, ongoing CSM (of both improved and traditional stoves) allow field staff to see which stoves are being used/not used, and follow up with targeted after sales service to fix issues and keep users satisfied and ensure long term adoption. Even monitoring in a subset can help a distributor or implementer evaluate the efficacy of the overall program delivery.

Follow-Up/Future Objectives: Better define the logistics, costs, staff requirements, and feasibility of large-scale sensor distribution and management.

Example: After 17 months of ongoing monitoring, one intervention discovered that stove usage dropped by nearly 50% across households of very similar characteristics. Monthly usage data revealed one user with a forced draft stove equipped with a CSM had been using her forced draft stove on average 4 hours per day. Within 3 months, the CSM showed her usage slowly decreasing and eventually dropping to 0 hours a day. The implementing NGO made a follow-up visit to the household and found that the internal combustion chamber was damaged and while it was still functional, she no longer preferred this stove over her traditional stove. The NGO sent a technician (Locally person trained to make basic repairs that do not require the manufacturer's assistance) to the household to make the necessary repair, and the real-time data showed that the woman had resumed cooking almost immediately. However, 3 months later, the data showed a majority of households decreasing stove use, and follow-up visits revealed that there were too many households for the minimal available technicians to service, so the program needs to be re-designed to build sustainable infrastructure for after sales service at scale. Once this happens, CSM will be required to understand the impact of this re-designed program.

- Sample size: minimum 30 households with CSM, with targeted household visits and stove inspections (chosen based on sensor data) in half of homes.

- Duration of intervention: 3 months intervals for each iteration of the program (The suggestion here is to conduct rapid iterations of the program, using the CSM data and follow up surveys to understand improvements needed in the after sales service, then conduct another intervention with the improved design, and so on).

- Frequency of data collection: CSM recording every 10 minutes for entire intervention. Targeted household visits every 3 months for the first year and on an as needs basis for subsequent years, and stove inspections every 6 months for the first 2 years and on an as needs basis for subsequent years.

- Speed of data accessibility: within 24 hours.

C. Thematic Area 3: Monetizing benefits via Results-Based Financing

a. Climate Benefits

b. Health Benefits

For results based financing – project implementers can be paid for emissions reductions commensurate with their clean cookstove usage, as determined by the CSM. With the addition of Personal Exposure Monitoring (PEM) on a subset of homes, the ADALYs can be calculated and used to generate health impact credits (which can be kept by the project implementer or paid to users). The methodology for this has been described in detail by the Gold Standard Foundation. Near-real time data collection is critical for this application, in order to make payments on time.

Example: Investors wish to finance the distribution of 10,000 clean stoves, but want to invest in the results of the program. By collecting stove usage and/or $PM_{2.5}$ data, the health and climate impacts (in terms of CO_2e emissions reductions and ADALY's generated, respectively) can be quantified and used as the basis for payments to the project implementer.

- 100% of homes with CSM for entire duration of the intervention if providing usage based climate credits. For health impacts (ADALYs), 48 hour PEM samples shall be conducted in TBD homes annually, with gravimetric colocation in TBD homes, in accordance with the GSF methodology. (TBD = Waiting to adopt from GSF decision)
- Duration of monitoring: 1-2 year intervals (or period required by GSF methodology).
- Frequency of data collection: CSM recording every 10 minutes for entire intervention. Optical PEM instruments recording every 10 minutes. Gravimetric instruments set to 48 hour samples.
- Speed of data accessibility: 24 hours for stove usage data. 2-3 months for PEM data.

IV. INTERVENTION CONSIDERATIONS

This is an attempt to consolidate all the information we've gotten from this working group to date.

Important to first define what data is needed and how it will be used.

A. Stove Adoption

Traditional stoves should be monitored whenever possible to give the most complete picture of cooking in the households. However, at a minimum, only improved stove monitoring is required.

All stoves in the household should be monitored if the implementer wishes to:

- pinpoint the sources of PM 2.5 and other emissions
- make claims with confidence about displacement of traditional methods (unless baseline data is available on the average cooking duration of the traditional cookstove)

B. Variability in fuel mixture

To the extent possible, fuel mixture should be kept constant, and individual surveys should ask about the mixture to understand if changes are occurring.

C. Variability by location

The boundaries of each intervention shall be clearly defined with the understanding that the findings only apply to the region with the same climate and cooking behaviors.

D. Qualitative metadata

Stove usage information is much more useful when combined with qualitative metadata. Yet there must also be standardization of the metadata so that different interventions can be compared to each other. The following 10 questions shall be included in any survey, with others to be added as desired. **The following questions were selected from the AIREC clean cooking tool and Dharma Life user acceptance trial questionnaire.**

- Household size
- Type of house
- Primary livelihood of family
- Approximate household income
- Amount of time spent collecting fuel each week
- Amount of money spent on cooking fuel each week
- How many times do you cook per day?
- Preference between roasting, boiling, or frying.
- What stoves are currently in the house?
- Does the household have electricity?

E. Data sharing and privacy

Households participating in interventions shall give written or verbal consent that their data may be shared in anonymous or aggregated form. **Individual data with personal identifying information (e.g. name, village) shall never be shared.**

F. Cookstove lifespan

The lifespan of a cookstove shall be measured in terms of hours of use (as determined by CSM data) rather than years of deployment. For example, a stove which has been in a household for 18 months and has been used for a total of 950 hours, shall have an age of 950-hours. This will allow for better comparability between datasets, as stove degradation occurs primarily as a function of cooking time, not absolute time.

G. Sensor Placement – TBD

H. Add-Ons - Are there add-ons that can increase the utility of the sensors for the women (SMS, etc)? - TBD

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World Bank Nexleaf India HAP Sampling Protocol, 2016

Objective: This protocol outlines the steps to deploy, collect, and prep the instrumentation for collecting kitchen samples of particulate matter.

Materials:

Aircheck Pumps and chargers
BGI Triplex Cyclones
BGI Calibration Cap
Loaded 37mm filter cassettes.
Flowmeter
PATS+
Micro USB cable
Zero box and pump
Ziploc bag free from punctures or holes
Aluminum foil
Powder free gloves
Cotton swabs and Kimwipes
Cleaning alcohol
Laptop computer with Windows
Tape
Scissors
Powder free gloves
Luer tip adapters
hanging cord
zip ties
Cooler bags
Frozen water bottles
Tygon tubing

General:

- Installations will be made to collect two events cooking events per day.
- Prepare equipment, program instrumentation, and fill in forms as much as possible before arriving at home.
- When greeting participant, understand what is involved, and answer any questions.
- **Anytime you come back from the field, charge your pumps, flowmeters, and PATS+ so they are ready to go upon your return.**
- **Make sure your form is complete and not missing any information before leaving a home**

1) Zeroing and launching
REMEMBER: PATS+ needs to be zeroed before AND after a measurement.
   - The PATS+ gets launched by the computer first, then zeroed. After the zero, it is live and ready to be placed.
   - Before the PATS+ starts sampling, it must be in a zero-particle environment for 10 minutes.
   - At the sampling location, find a clean, safe area out of direct sunlight.
   - Launch the PATS+ using the PICA computer application
      - Plug in the PATS+ using a regular the micro-USB cable

    - In the Launch tab, select the sampling interval (300 seconds in this case)
    - Click sync launch
    - Unplug the PATS+ and confirm it is in standby mode (double blinking red)
- Press and hold the PATS+ button until you see the red light appear and then change to green. Once the light is green, release the button.
- Check that the PATS+ indicator LED is flashing orange (*once per second*) and place it in the zero box with the intake hole exposed. The orange indicator means that it is in the zeroing mode, which will last for 10 minutes.
- Repeat as quickly as possible for up to 4 PATS+ units (this is the maximum that will fit in a zero box).
- Close the box and pump 36 squeezes of air into the box (through the intake hole), using the squeeze pump.
- After 10 minutes (or when you see that the PATS+ light is flashing green), open the box and check that the light is flashing green *every two seconds*. It is now in sampling mode and actively collecting data.

2) Installation
   a) Kitchen equipment should be installed 1.5 meters from the ground and 1 horizontal meter from the center of the stove. Attempt to avoid placing equipment next to doors, windows or other openings. Also make sure it is not in a place where the emissions plume will flow directly through the equipment. Check that it will not interfere with the participant's activities.
   b) PATS+
      i) After zeroing is complete, the PATS+ are live and ready to be placed.
      ii) After placement, ensure that the green light is flashing. Note the time that you placed it, and that you performed an initial zero and checked the green light on the sampling form.

   c) Gravimetric system
      i) Select a filter cassette and connect the vacuum leak check pump to the inlet of the filter. Squeeze the vacuum pump and the pressure level should not change. If there is a leak, press the cassette together and recheck. If there is still a leak, use a different filter cassette.
      ii) Note the filter ID on your survey form and write the household ID and the date on the label on the filter cassette, note ID of blank filter as well, if using.
      iii) Attach the tubing from the suction inlet on pump to bottom of the filter cassette.
      iv) Place the calibration cap on the cyclone and attach tubing from the calibration cap to the suction point on the flow calibrator and turn the calibrator on.
      v) Turn on the AirChek pump by pressing and holding the center button (see pump protocol for more detailed directions).
      vi) Adjust the pump until the calibrator reads between 1.45 and 1.55 L/min. Record the flow in the survey form.
      vii) Turn the pump off and remove the calibration cap.
      viii) Place pump in the cooler bag with the filter and cyclone hanging out of the cooler bag.
      ix) Turn the pump on when leaving the household and note this as the start time for the sample (for all instruments).

d) Write sample ID number on whiteboard or paper and take photographs that show detail of sampling equipment IDs and placement instrumentation. Take a closeup of the sampling equipment, and another photo that shows the sampling equipment and stove in the same shot.

3) Measuring the kitchen
   a) You can take the kitchen measurements whenever you like, before or after placing the sensors.

4) Takedown
   a) PATS+
      i) Takedown the PATS+ and record the stop time. Press the button until it is green, and place the PATS+ back in the zero chamber. Pump clean air into it 36 times, and wait 10 minutes.
   b) Gravimetric
      i) Stop the pump and record the stop time and total run duration.
      ii) Take the final flow rate using the flowmeter and record it
      iii) Unplug the tube from the cassette and replace the cab.
      iv) Put on a pair of powder free gloves.
      v) Use a coin to remove the cyclone, then quickly squeeze the cassette cap on
      vi) Cover the cassette in tin foil, then place in a small plastic zip bag and seal.
      vii) Place the bag inside the icebox.

5) Downloading Data
   - Connect the device to the computer using USB micro cable.
   - Open PICA software and select 'PATS+' page and select the baud rate (115200).
   - Then Press 'Reset' button from the 'PATS+' page and you should see a prompt (a pound sign) in the command window after a few moments.
   - Click on the filename which you want to download from the 'PATS+' page and press 'Upload'.
   - You should see that the graph and the 'Selected file details' have updated after a few moments.
   - Then click on the Data tab, you should have the file you selected from the Pats+ page.
   - To see all the graphs, go to 'Data' tab and you can select from the options on the left side of the graph to view the various graphs.
   - To download the file, click the 'Save to Excel' button.
   - Select a location where you want to save the file.
   - Then click the 'save' button and the file will be saved at the selected location.
   - Rename the file as needed.
   - After each day of data is downloaded, turn the entire file into a zip file and email to the project manager.

6.) When you get back from the field:
   a) Place the cassettes in the freezer
   b) Charge all devices
   c) Clean grit pot of cyclone using cotton swabs and methanol

World Bank Nexleaf India HAP Sampling Protocol, 2016

Objective: This protocol outlines the steps to deploy, collect, and prep the instrumentation for collecting kitchen samples of particulate matter.

Materials:

Aircheck Pumps and chargers	Cotton swabs and Kimwipes
BGI Triplex Cyclones	Cleaning alcohol
BGI Calibration Cap	Laptop computer with Windows
Loaded 37mm filter cassettes.	Tape
Flowmeter	scissors
Special HAPEx Micro USB cable	Luer tip adapters
Zero box and pump	hanging cord
HAPEx	zip ties
Ziploc bag free from punctures or holes	Cooler bags
Aluminum foil	Frozen water bottles
Powder free gloves	Tygon tubing

General:

- Installations will be made to collect two events cooking events per day.
- Prepare equipment, program instrumentation, and fill in forms as much as possible before arriving at home.
- When greeting participant, understand what is involved, and answer any questions.
- Anytime you come back from the field, charge your pumps and flowmeters so they are ready to go upon your return.
- Make sure your form is complete and not missing any information before leaving a home

1) Zeroing and launching
   •Zeroing
      •The HAPEx gets zeroed first (initiated by the computer) and then needs to be pugged back into the computer to be launched.
      •Plug the HAPEx into the computer using the special (longer) USB cable
      •Open the HAPEx launcher software
      •Select the device from the menu at the top (it may be com4, or another name). Wait until it says connection established.
      •Click Zero
      •Click Start

•Place it in the zero box with the intake holes exposed. Close the box and pump 36 squeezes of air into the box (through the intake hole), using the squeeze pump.

•Launching

•After zeroing, plug the HAPEx back into the computer using the special USB cable

•Click Mission, and set the sampling interval to the appropriate amount (in this case select 4.7 minutes)

•Click Start

•Observe the first few readings (every 20 seconds) to make sure they look reasonable and are changing. Sometimes it gets stuck on the same number. If that happens, relaunch the mission.

•Unplug the HAPEx.

•Note the time that you launched the HAPEx.

2) Installation
   a) Kitchen equipment should be installed 1.5 meters from the ground and 1 horizontal meter from the center of the stove. Attempt to avoid placing equipment next to doors, windows or other openings. Also make sure it is not in a place where the emissions plume will flow directly through the equipment. Check that it will not interfere with the participant's activities.
   b) HAPEx
      i) Ensure that neither of the holes are obstructed when it is placed. Note the time that you placed it on the sampling form.

   c) Gravimetric system
      i) Select a filter cassette and connect the vacuum leak check pump to the inlet of the filter. Squeeze the vacuum pump and the pressure level should not change. If there is a leak, press the cassette together and recheck. If there is still a leak, use a different filter cassette.
      ii) Note the filter ID on your survey form and write the household ID and the date on the label on the filter cassette, note ID of blank filter as well, if using.
      iii) Attach the tubing from the suction inlet on pump to bottom of the filter cassette.
      iv) Place the calibration cap on the cyclone and attach tubing from the calibration cap to the suction point on the flow calibrator and turn the calibrator on.
      v) Turn on the AirChek pump by pressing and holding the center button (see pump protocol for more detailed directions).
      vi) Adjust the pump until the calibrator reads between 1.45 and 1.55 L/min. Record the flow in the survey form.
      vii) Turn the pump off and remove the calibration cap.
      viii) Place pump in the cooler bag with the filter and cyclone hanging out of the cooler bag.
      ix) Turn the pump on when leaving the household and note this as the start time for the sample (for all instruments).
   d) Write sample ID number on whiteboard or paper and take photographs that show detail of sampling equipment IDs and placement instrumentation. Take a closeup of the sampling equipment, and another photo that shows the sampling equipment and stove in the same shot.

3) Measuring the kitchen
   a) You can take the kitchen measurements whenever you like, before or after placing the sensors.

4) Takedown
   a) HAPEx
      i) Takedown the HAPEx, plug it into the computer, launch the HAPEx software, and click stop.
   b) Gravimetric
      i) Stop the pump and record the stop time and total run duration.
      ii) Take the final flow rate using the flowmeter and record it
      iii) Unplug the tube from the cassette and replace the cab.
      iv) Put on a pair of powder free gloves.
      v) Use a coin to remove the cyclone, then quickly squeeze the cassette cap on
      vi) Cover the cassette in tin foil, then place in a small plastic zip bag and seal.
      vii) Place the bag inside the icebox.

5) Downloading Data
   a) HAPEx
      i) Connect to computer and open software
      ii) Click stop
      iii) Click save as xml

6.) When you get back from the field:
   a) Place the cassettes in the freezer
   b) Charge all devices
   c) Clean grit pot of cyclone using cotton swabs and methanol

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

A. IDENTIFICATION INFORMATION		
A1	Household ID	
A2	Village	
A4.1	Initials of field technicians	
A4.2		
A4.3		
A5	Date of initial visit (YY/MM/DD, i.e. 15/03/30)	__ __/__ __/__ __
A6	Start time of initial visit (Use 24 hour clock, i.e. 17:48)	__ __:__ __
A7	Date of follow-up visit (YY/MM/DD, i.e. 15/03/30)	__ __/__ __/__ __
A8	Start time of follow-up visit (Use 24 hour clock, i.e. 17:48)	__ __:__ __
A9	Primary cooking stove in kitchen (to be monitored)	Trad Chulha / Rocket / LPG
A10	Other stoves used in home (circle all that apply)	Trad Chulha / Rocket / LPG / Other

B. KITCHEN SETUP					
B1	Instrumentation distance from ground (m)				
B2	Instrumentation distance from center of stove (m)				
B3	Location of kitchen		1 = Separate building 2 = Separate kitchen attached to rest of main house 3 = Main living area in house		
B4	Is the kitchen…		1 = Enclosed 2 = Semi-open 3 = Has an unfinished wall between kitchen and the other room 4 = Has wire mesh around the kitchen		
B5.1	Kitchen Dimensions		Length (m)		
B5.2			Width (m)		
B5.3			Diameter (m) [if round kitchen]		
B5.4			Height1 (maximum) (m)		
B5.5			Height2 (minimum) (m)		
B6.1	Door Dimensions in kitchen Door 1			Length (m)	
B6.2				Width (m)	
B6.3	Door Dimensions in kitchen Door 2 (if there is a second door)			Length (m)	
B6.4				Width (m)	
B7.1	*(If more than two windows, choose largest ones)*	Open Window Dimensions of window in kitchen- Window 1		Length (m)	
B7.2				Width (m)	
B7.3		Open Window Dimensions of window in kitchen - Window 2		Length (m)	
B7.4				Width (m)	

WB Nexleaf – INDIA

B8	Is the kitchen …	1 = Bright and airy 2 = Normal 3 = Dark and enclosed	

KITCHEN MATERIALS

1	*Mud bricks*	**6**	*Wattle (woven sticks)*	**11**	*Stone and wood*
2	*Fired bricks*	**7**	*Wattle & mud/clay/ dung)*	**12**	*Concrete/cement*
3	*Mud/clay/dung*	**8**	*Wood*	**13**	*Other*
4	*Woven reed*	**9**	*Corrugated iron*		
5	*Thatch*	**10**	*Stone*		

B9.1	What is the roof made of in the kitchen with the main stove?	
B9.2	If 'other' please specify	
B10.1	What are the walls made of in the kitchen with the main stove?	
B10.2	If 'other' please specify	
B10.3	Notes	

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

C. KITCHEN EQUIPMENT PROGRAMMING – Visit 1			
*NOTE: * = Values recorded before field deployment*			
	Kitchen - Gravimetric		
	Installation visit		
C1	** Filter ID*		
C1.1	** Blank Filter ID (if using)*		
C2	** Pump ID*		
C3	Initial Flow Rate (L/min)		
C4	Pump Start Time (hh:mm)		
	Take-down visit		
C5	Final Flow Rate (L/min)		
C6	Final Run Duration (min)		
C7	Stop Time (hh:mm)		
	Kitchen – PATS+		
	Installation Visit		
C8	** Instrument ID*		
C8.8	Performed Initial Zero and Checked for Green light? (y/n)		
C9	Start Sample Time (hh:mm)		
	Take-down Visit (IF REPLACING PATS+)		
C10	Sample Stop Time (hh:mm)		
C10.1	Green Light and Fan On? (y/n)		
C10.2	Performed Final Zero? (y/n)		
	Kitchen – HAPEX		
	Installation Visit		
C11	*Instrument ID*		
C12	Launch Time		
C13	Start Sample Time (hh:mm)		
	Installation Notes		
C14	**Picture Taken (y/n)**		
C15	Notes		

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

D. FOLLOW-UP QUESTIONS – Visit 1		
D1	Did any of the tubes become disconnected or were there any other problems?	
D2	How often did someone smoke in the kitchen since the last visit?	1. Never. 2. 1-2 times. 3. 3 or more times.
D3	Were any other sources of smoke besides your stoves or tobacco smoking in the kitchen?	1. Neighbour's stove 2. Trash burning 3. Kerosene lamp 4. Other (please describe)______________

Stove Use Events

What have your stoves been used for since the last visit? Please include all tasks such as re-heating food, heating your home, warming bath water, heating drinks, etc as well as all cooking events.
If they use more stoves please record multiple for each event]

Codes for events		Codes for stoves
1 Initial cooking of meals	4. Space heating	1. Traditional Chulha (TC)
2. Re-heating food	5. Other_____________	2. Rocket Stove (RS)
3. Tea/hot drinks		3. LPG
4. Heating water		4. Other:_______________

	D4	D5	D6	D7	D8	D9	D10
Event							
Stoves used							

D11 Notes on stove use from previous day (record anything that was unusual such as parties, running out of fuel, sweeping, damage to equipment, malfunctions, etc….)

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

A. KITCHEN EQUIPMENT PROGRAMMING – Visit 2		
*NOTE: * = Values recorded before field deployment*		
	Kitchen - Gravimetric	
	Installation visit	
E1	* *Filter ID*	
E1.1	* *Blank Filter ID (if using)*	
E2	* *Pump ID*	
E3	Initial Flow Rate (L/min)	
E4	Pump Start Time (hh:mm)	
	Take-down visit	
E5	Final Flow Rate (L/min)	
E6	Final Run Duration (min)	
E7	Stop Time (hh:mm)	
E8	Is the PATS+ Green Light and Fan On? (y/n)	
E9	Notes	

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

F. FOLLOW-UP QUESTIONS – Visit 2		
F1	Did any of the tubes become disconnected or were there any other problems?	
F2	How often did someone smoke in the kitchen since the last visit?	4. Never. 5. 1-2 times. 6. 3 or more times.
F3	Were any other sources of smoke besides your stoves or tobacco smoking in the kitchen?	1. Neighbour's stove 2. Trash burning 3. Kerosene lamp 4. Other (please describe)_____________

Stove Use Events

What have your stoves been used for since the last visit? Please include all tasks such as re-heating food, heating your home, warming bath water, heating drinks, etc as well as all cooking events.
If they use more stoves please record multiple for each event]

Codes for events		Codes for stoves
1 Initial cooking of meals	4. Space heating	1. Traditional Chulha (TC)
2. Re-heating food	5. Other____________	2. Rocket Stove (RS)
3. Tea/hot drinks		3. LPG
4. Heating water		4. Other:______________

	F4	F5	F6	F7	F8	F9	F10
Event							
Stoves used							

F11 Notes on stove use from last visit (record anything that was unusual such as parties, running out of fuel, sweeping, damage to equipment, malfunctions, etc….)

Household ID: Initial Visit Date:

WB Nexleaf – INDIA

A. KITCHEN EQUIPMENT PROGRAMMING – Visit 3		
*NOTE: * = Values recorded before field deployment*		
	Kitchen - Gravimetric	
	Installation visit	
E1	* *Filter ID*	
E1.1	* *Blank Filter ID (if using)*	
E2	* *Pump ID*	
E3	Initial Flow Rate (L/min)	
E4	Pump Start Time (hh:mm)	
	Take-down visit	
E5	Final Flow Rate (L/min)	
E6	Final Run Duration (min)	
E7	Stop Time (hh:mm)	
	Kitchen – PATS+	
	Take-down Visit	
E8	Sample Stop Time (hh:mm)	
E9	Green Light and Fan On? (y/n)	
E10	Performed Final Zero? (y/n)	
	Kitchen – HAPEX	
	Take-down Visit	
E11	Sample Stop Time (hh:mm)	
E12	Notes	

F. FOLLOW-UP QUESTIONS – Visit 3		
F1	Did any of the tubes become disconnected or were there any other problems?	
F2	How often did someone smoke in the kitchen since the last visit?	1. Never. 2. 1-2 times. 3. 3 or more times.
F3	Were any other sources of smoke besides your stoves or tobacco smoking in the kitchen?	1. Neighbour's stove 2. Trash burning 3. Kerosene lamp 4. Other (please describe)_____________

Stove Use Events

What have your stoves been used for since the last visit? Please include all tasks such as re-heating food, heating your home, warming bath water, heating drinks, etc as well as all cooking events.
If they use more stoves please record multiple for each event]

Codes for events		Codes for stoves
1 Initial cooking of meals	4. Space heating	1. Traditional Chulha (TC)
2. Re-heating food	5. Other____________	2. Rocket Stove (RS)
3. Tea/hot drinks		3. LPG
4. Heating water		4. Other:______________

	F4	F5	F6	F7	F8	F9	F10
Event							
Stoves used							

F11 Notes on stove use from last visit (record anything that was unusual such as parties, running out of fuel, sweeping, damage to equipment, malfunctions, etc.…)

Memo on using kitchen particulate matter (PM) concentration measurements to estimate ADALYs

From kitchen particulate matter (PM) concentration measurements to personal exposure estimates:

The air pollution inputs required for the HAPIT model to estimate ADALYs are personal exposure to particulate matter ($PM_{2.5}$) for both the baseline and project (new) stove scenarios. 24-hour mean kitchen PM concentration measurements from real-time light scattering monitors can be adjusted to estimate personal exposure in a two-step process.

First, the real-time PM instrument response is corrected based on the relationship with a subset of reference PM measurements. The real-time instruments measure particle concentrations by detecting the light that scatters off the particles in a sensing chamber. Particles, however, will have different optical properties depending on their size, shape, and color, which can change depending on their source and age. To account for the instrument's response to particles generated for given project site, a set of co-located samples is collected using gravimetrically-based particulate measurement systems (the reference measurements). The co-located samples are then plotted and regressed to determine the adjustment factor to be applied to normalize the real-time light scattering instrument response to the reference measures. Once the correction factor is applied, the real-time responses are considered calibrated to provide estimates of particulate mass concentrations in the kitchen.

To estimate the personal exposures based on kitchen concentrations, a reliable ratio of personal exposure-to-kitchen concentrations needs to be established. This approach was used by the Global Burden of Disease study to estimate exposure from indoor air pollution (Smith et al., 2014), and Balakrishnan et al. 2004 found that 24-hour mean exposures were well-correlated with kitchen concentrations (r^2=0.77) for a study in South India (Balakrishnan et al., 2004). Ideally, the personal exposure-kitchen ratio is established on a project basis to provide the most representative estimate, and guidance on how to conduct such sampling is provided below. In the absence of project-specific data to establish the ratio, literature-based values may be used. In the case of India, the work by Balakrishnan et al. 2004 provides evidence of a strong relationship, and ratios for India were published by the World Health Organization's Air Quality Guidelines: Household Fuel Combustion (0.742 for women, 0.628 for young children, and 0.450 for men) (Balakrishnan et al., 2014).

HAPIT uses this same ratio data from India to estimate the personal exposure for other household members based on the input exposure estimates for the primary cook, following methods used to calculate impacts in the IHME Global Burden of Disease project (Smith et al., 2014; WHO, 2014). Thus, HAPIT uses a default non-cook adult to primary cook exposure ratio of 0.60 and a child to primary cook exposure ratio of 0.85
(GS methodology draft 6, p 16).

Guidance for determining the project-specific personal exposure-kitchen ratio

We recommend doing at least 15 sets of simultaneous 24-hour measurements of personal exposure to PM of main cooks and kitchen PM concentrations for each sub-group. That is, measure both PM personal exposure and kitchen PM concentrations for 24-hours in at least 15 different baseline households and in at least 10 different project stove households, yielding an estimate of the ratio for both scenarios. The PM measurement devices must be the same for exposure as for kitchen concentrations to ensure comparability, but either real-time light scattering monitors or gravimetric pump-and-filter systems would be appropriate. The personal-kitchen ratio should be calculated for each household, and the mean of the ratios should be determined for each sub-group.

HAPIT methodology and inputs:
(taken directly from "Methodology to Estimate and Verify Averted Mortality and Disability Adjusted Life Years (ADALYs) from Cleaner Household Air," draft 6, Gold Standard Foundation, October 2016)

1. HAPIT methodology and inputs

HAPIT estimates averted deaths and ADALYs from user-specified baseline and project $PM_{2.5}$ exposures using epidemiology-derived exposure-response functions and information about population demographics and health characteristics (Pillarisetti et al., 2016). The specific methods underlying HAPIT are detailed in Annex 4. HAPIT calculates the disease burden attributable to PM2.5 exposures before and after the project is implemented, and subtracts them to obtain the disease burden averted by the project. HAPIT uses national background health data for the year 2013 (subnational for China and Mexico) and methods and databases developed as a part of the Comparative Risk Assessment, a component of the IHME's Global Burden of Disease Study (GBD) (Lim et al., 2012). HAPIT relates PM2.5 exposure to disease burden using Integrated Exposure Response (IER) functions for the major disease categories associated with PM2.5 exposure (Burnett et al., 2014).

The five major disease categories for which HAPIT estimates ADALYs are:

- Ischemic heart disease (IHD)
- Stroke
- Chronic obstructive pulmonary disease (COPD)
- Lung cancer
- Child (under 5 years) acute lower respiratory infection (ALRI)

The IERs provide exposure-response relationships across the entire range of $PM_{2.5}$ exposures (up to 1000 $\mu g/m^3$) for each of these health endpoints. See Annex 4 for more details.

HAPIT will be updated regularly as per GBD updates, as new evidence on health effects becomes available and population demographics change. These changes may increase or decrease the ADALYs per unit reduction in $PM_{2.5}$. Project developers will be issued ADALYs that are estimated by the version of HAPIT in use at the time of requesting issuance of ADALYs certificates.

HAPIT uses a variety of input parameters to estimate averted deaths and ADALYs. Parameters that are hard-wired into HAPIT and cannot be altered by the project developer include exposure-response functions, population, and baseline disease incidence rates (see Annex 4 and Table 1).

Parameters that are required to be monitored and input by the project developer include baseline and project $PM_{2.5}$ exposures, number of targeted households, fraction of targeted households using the intervention, percentage of project population using solid fuels and the useful intervention lifetime (

Table 1). The user must also input the country where the project is located to use the appropriate national or subnational baseline health data. Projects in China and Mexico shall input the province or state where the project is located to use the subnational baseline health data published by the GBD study.

Table 1. User-defined parameters required to run the HAPIT tool, along with their units and data sources.

Parameter	Units	Data Source
Country or province/state where project is located	Country or province/state name	Country or province/state where the project is located
Baseline $PM_{2.5}$ exposure	μg/m³	PEM or alternative methods detailed in Section XX
Project $PM_{2.5}$ exposure	μg/m³	PEM or alternative methods detailed in Section **Error! Reference source not found.**
Number of targeted households	#	Number of households targeted for inclusion in the intervention (includes households not utilizing the technology)
Number people per household	#	Household surveys or HAPIT default
Percentage of project population using polluting fuels ($PFU_{fraction}$)	%	Household surveys
Number children per household age under 5 years	#	Household surveys or HAPIT default
Fraction of targeted households using intervention (usage rate)[1]	# (0 to 1)	Household surveys and/or stove use monitoring (Section XX
Useful intervention lifetime	# years	Manufacturer specification

Outputs from HAPIT are the reduction in mortality and DALYs among the population from reduced $PM_{2.5}$ exposure achieved during *each year* of the project's operation. As HAPIT runs in full calendar year increments, results output by HAPIT shall be multiplied by the weighted average fraction of days of the year during which the project stoves were operational. Long-term health benefits associated with each year's exposure reduction are still included in the annual estimates and will be awarded to the project in the year exposure was reduced (i.e. for exposure reduction in year 2016, associated health benefits in year 2016-2020 are awarded in 2016). ADALYs and avoided mortality will be awarded to projects each year of the project's lifetime using the monitored exposures and usage rates as per monitoring

[1] Does not account for the fraction of baseline technology use that is displaced by the new technology. In other words, usage fraction incorporates any household using the new technology at all, regardless of how much the new technology is used and how much the baseline technology is used.

requirements. These benefits would be expected regardless of whether exposure levels return to baseline in the next year. For conservativeness, HAPIT will calculate health benefits for only the five years following a one-year exposure reduction, or 80% of the total health benefits that would be expected over the 20 years following the one-year exposure reduction based on US EPA cessation lag. The total health benefits for the project are the sum of the 5-year health benefits accrued for each year of exposure reduction (i.e. 5-year health benefits for exposure reduction in 1 year + 5-year health benefits for exposure reduction in year 2, and so on through the project's lifetime).

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