
# LESSONS LEARNED FROM SENSOR-BASED MONITORING OF LIQUID FUEL STOVES IN NIGERIA

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<u>**Lessons learned from sensor-based monitoring of liquid fuel stoves in Nigeria**</u>

## Introduction

Nexleaf Analytics has been developing and testing sensor technology to monitor cooking since 2010. For many years, Nexleaf has applied its Stovetrace technology to improved biomass stoves as well as traditional stoves for comparative cooking. In 2019, Nexleaf applied Stovetrace to liquid fuel stoves—LPG, ethanol, and ethanol gel—for the first time as part of a pilot project in partnership with Rural Women Energy Security (RUWES) and with support from the Climate and Clean Air Coalition (CCAC). The pilot involved the distribution of 5 stove types to 50 women (10 women per stove) and a 6-month monitoring period using Stovetrace. The pilot aimed to identify the most reliable stoves for rural Nigerian women, and offered valuable lessons-learned on how sensors can play a role in clean cooking data collection. Data from the pilot was also used to calculate total household emissions, providing evidence of the need to integrate data into clean cooking programs and to look beyond distribution when measuring impact.

*The Stovetrace sensor and Trek data logger attached to an LPG stove in Nigeria. The sensor is attached to the stove via an iron bar, which conducts heat to the sensor when the stove is in use. Treks were similarly attached to ethanol and improved biomass*

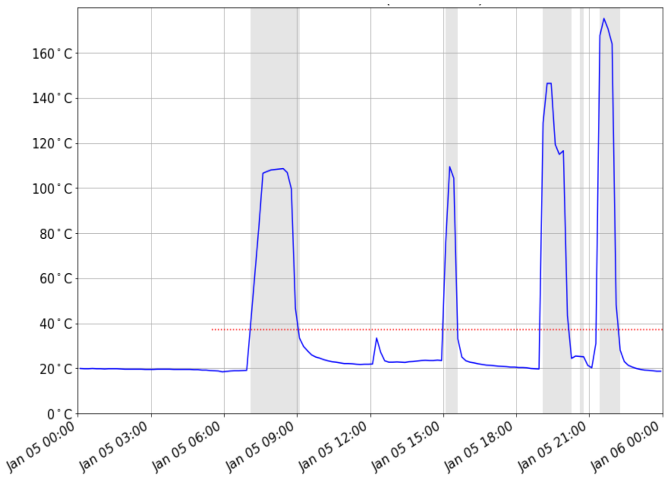
### *Background: How sensor monitoring works*

Nexleaf's Stovetrace monitoring works by attaching a temperature sensor and the "Trek" data logger to the stove. The sensor and data logger collect and store data passively, requiring nothing from the household other than keeping the sensor in place, or returning it to place after stove cleaning. The sensor sends temperature readings from the stove to the Trek data logger every 10 minutes, and the Trek stores that information. Data from the Trek is collected via bluetooth using the Stovetrace mobile application, and then sent to the server where it is processed and visualized. Cooking is calculated through an event detection system that distinguishes between ambient and cooking temperatures based on a temperature threshold. The dynamic threshold model is based on a gaussian mixture model, which groups data into two separate normal distributions. The model forms a bimodal distribution of two distinct subpopulations that consist of ambient temperatures and cooking temperatures. Historical temperature data allows for a cooking threshold temperature to be acquired, which is tuned specifically to each household using statistical modeling.

*A traditional 3 Stone Fire in Nigeria. 3SF were also monitored using Stovetrace. Here a longer iron bar is inserted into the fire, conducting heat to the sensor which remains away from direct flames.*

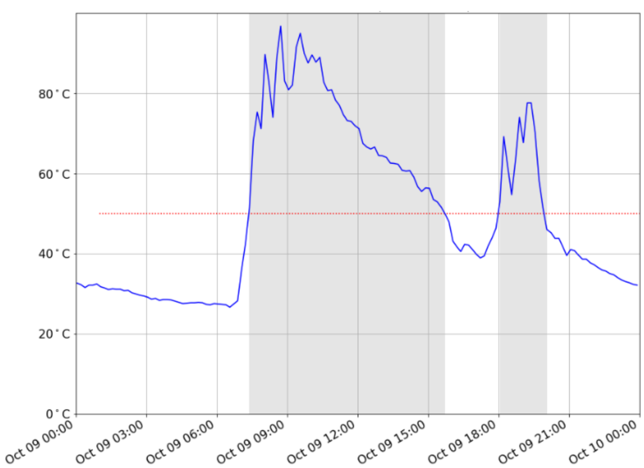
***Data yielded from LPG and other cooking***

As with other types of cookstoves, temperature data is used to identify when cooking occurs and for what lengths of time. Because of the rapid heating and cooking time of LPG and other liquid fuel stoves, cook times are even more easily identified using temperature data than with biomass stoves. Sensors are therefore a promising way to accurately measure and monitor cooking on liquid fuel stoves.




*A temperature and cooking graph from an LPG stove. Temperature spikes are easily identified as cooking (gray area indicates time identified as cooking time), providing clean, accurate data for analysis and interpretation.*

The data yielded through temperature sensors and the Stovetrace method of cooking detection produces three types of measurements: 1. Minutes spent cooking, 2. Count of cooking events, and 3. Time of day that cooking occurs. Nexleaf has used minutes of cooking as a way to measure usage and adoption of stoves over time, and as a way to compare usage between different stove types, such as improved stoves vs. traditional stoves, and between two different models of improved cookstoves. Minutes of cooking can also be used in combination with data from stove emissions lab tests to estimate actual emissions from stoves. The following section explains how these calculations using cooking time are made and what implications they have for estimating actual stove emissions.




*Temperature data from the traditional 3 Stone Fire includes long cool down periods and temperatures that fluctuate during the cooking event. While sensors are still valuable for understanding traditional and improved biomass stove use, the division between cooking and not-cooking is less exact.*

## Emissions and Stove Stacking: How sensor data reveals total household black carbon emissions

Even the cleanest stoves will only achieve the desired impact on household air pollution if these stoves displace traditional cooking methods. As has been proven time and time again, stove stacking is extremely common and is influenced by a variety of factors including stove design and durability, regional culinary preferences, fuel supply, fuel cost, heating needs, and others. LPG and ethanol stoves are among the cleanest options in terms of household air pollutants, with negligible emissions of black carbon. These cleanest solutions also come with high fuel costs—especially in contexts where wood and traditional biomass sources have no cost other than the labor to acquire them—and require infrastructure to maintain a reliable fuel supply. While these stoves offer the highest *potential* benefit to household air quality, households have financial and logistical reasons *not* to use these clean stoves for all of their cooking needs, thus reducing their actual emissions impact.

In the Nigeria pilot, Stovetrace was used on both improved stoves and traditional stoves, offering an opportunity to measure *total* household emissions. The combined total emissions calculations demonstrate that the cleanest improved stove options do not necessarily translate into the smallest total household emissions. As long as TCS use continues to be high, even households with the cleanest solutions will continue to experience high combined household emissions. These calculations once again demonstrate why stove usage is so important to measuring cookstove impact.

***How BC emissions are calculated using cooking time***

Emissions are calculated by multiplying the time series data, which has unit time, by the emissions rate, which has unit kg/time, yielding kg of black carbon emissions. The emissions rate is calculated in lab tests, which measure black carbon collected on a filter during stove cold start, hot start, and simmer. Example:

$$kg/hr\ (rate) \times hr\ (time) = kg\ BC\ emitted$$

Suppose we have a stove with emissions rate $1.2 \times 10 - 6\ kg/hr$ and a time series of ICS data, we total that to get the total time which is $5000\ hr$, using the equation above, $1.2\ \times 10 - 6\ kg/hr\ \times 5000\ hr\ = .006\ kg$ , we are left with mass in $kg$s since time cancels out. This tells us the $kg$ of BC emitted during that time. This was calculated using the emissions rate for an LPG stove, hence total emissions are low.

The table below shows the stove types monitored in the pilot project as well as and BC emissions rates and sources. The simmer rate was used in cases where start rates were different from simmer.[1]

[1] On biomass stoves, the emissions rate can be significantly different during simmer than during start time, making emissions calculations during stove use in the field complicated. Assuming that start time is relatively shorter, the simmer rate was used for the biomass stoves in this calculation.

| Stove | BC Emissions rate (simmer) | Source |
|---|---|---|
| LPG | $2.7 \times 10{-}6$ | Shen et al. (Environ Sci Technol Jan. 2018), Johnson et al (Atmosphere May 2019), and Weyent et al (Physics 2019) |
| Natural Draft | $1.58 \times 10{-}4$ | Aprovecho Research Center |
| Ethanol | $1.5 \times 10{-}6$ | U.S. Environmental Protection Agency |
| Ethanol Gel | $1.5 \times 10{-}6$ | U.S. Environmental Protection Agency[2] |
| TEG Forced-Draft | $4.8 \times 10{-}4$ | Aprovecho Research Center |
| 3SF | $1.24 \times 10{-}3$ | Lawrence Berkeley National Laboratory |

Using cooking time and emissions calculations as described above, we calculated total household emissions from the full "stack" of household cooking: both the 3SF and ICS from the Nigeria pilot households. Figure 1. Shows total household emissions from both monitored stoves combined: the pilot clean cookstove and the traditional 3 Stone Fire together. As you can see, the BC emissions contribution from the clean fuel stoves (ethanol and LPG) is negligible, not even visible in the graph in comparison to the improved biomass stoves which still produce BC emissions by virtue of their biomass fuel. **Total household emissions among the clean-fuel households remains high, however, because TCS use remains high. Total household emissions are actually higher among the LPG and ethanol households than the TEG forced-draft improved biomass households, despite the emissions contributions of the TEG biomass stove**. Figure 2 shows total cook time per pilot group per stove type, displaying differences in both TCS and ICS use across stove types, and the clear relationship between TCS use and total BC emissions in Figure 1.

[2] Emissions for ethanol gel stove inferred from emissions result of ethanol lab test.

**Figure 1.**

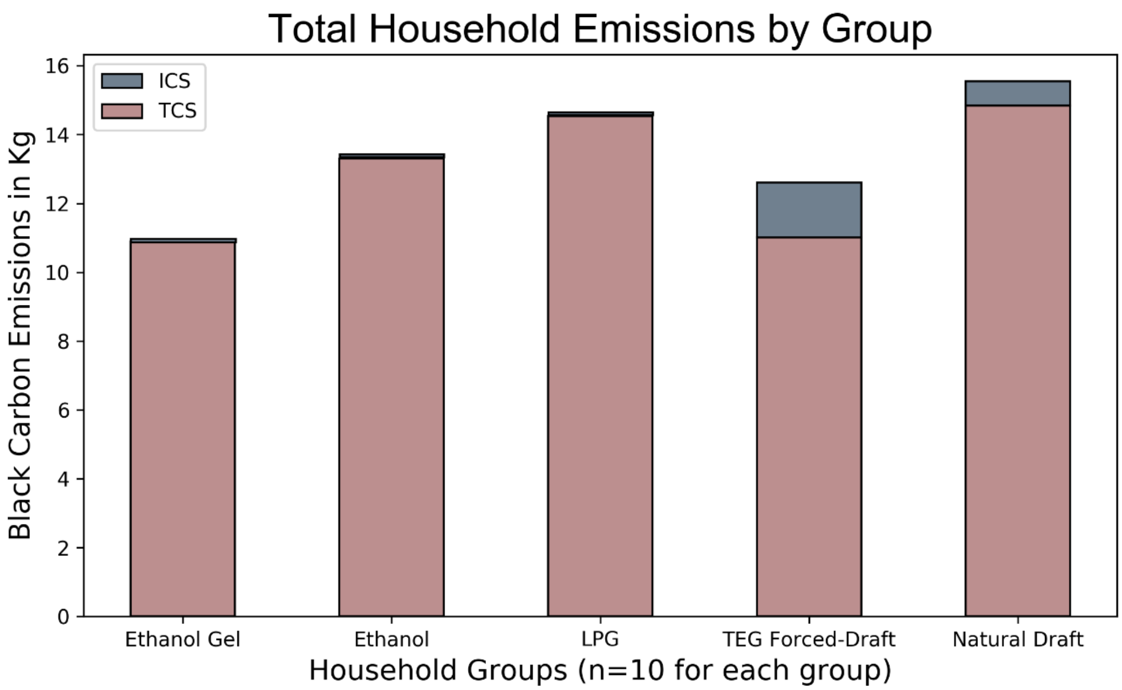
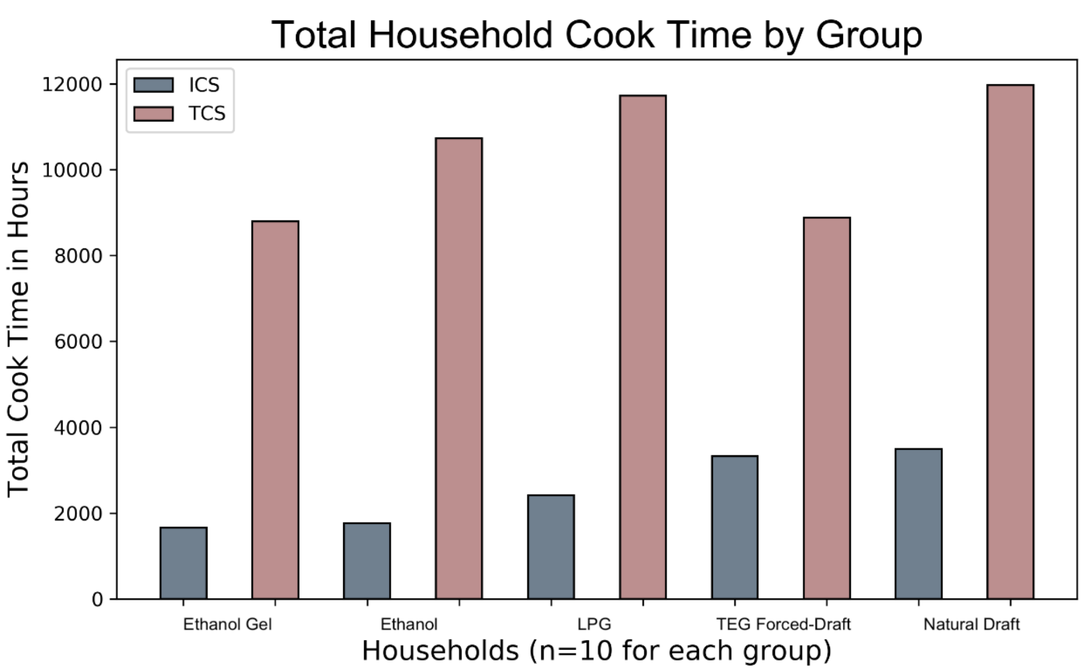



**Figure 2.**



Figures on total household emissions are not meant to serve as an evaluation of stove type or to indicate which ICS contributes to greater TCS displacement. The sample size per pilot group (n=10) is small and there is variability among and between the pilot groups in terms of household size and other factors that would affect overall TCS use. Rather, these calculations serve to provide evidence of the dynamic that is commonly understood but rarely directly measured: the introduction of an ICS won't make a significant difference to household air quality unless the chosen solution is reliable enough to displace TCS use.

**Conclusion: Use of sensors in clean cooking**

As described above, true impact can only be achieved when clean cooking solutions are reliable enough to displace traditional cooking. As with the calculations of total household emissions, sensor data can offer valuable insight into the persistence of TCS cooking. However, widespread or long-term TCS monitoring with sensors may not be practical. Sensor installation must be customized for each traditional cooking set up, and the placement of Treks in traditional cooking set ups is more likely to be intrusive to the households' cooking habits. The data itself is somewhat less reliable, as high fluctuations in cooking temperature are not as uniformly captured as cooking events. Furthermore, stove stacking usually applies to traditional cooking as well, as households in most contexts are likely to have not one but multiple traditional or un-improved stoves. Installing sensors on every stove in a household in order to measure stacking/displacement is likely only practical for short-term research studies or pre-post assessment for project evaluations.

Potentially more promising is the use of sensor data to identify the gaps in reliability that prohibit long-term and sustained usage of ICS, rather than measuring displacement (or lack thereof) itself. As explained earlier, temperature sensor data from clean-fuel stoves offers accurate and easy-to-interpret data on stove use while remaining relatively unobtrusive to the household and able to collect data continuously for long-periods of time. Sensors offer a way to objectively and relatively passively monitor stove use after distribution, especially in cases where other sources of usage data (such as fuel re-supply) are unavailable. This data can be used not only to assess whether stoves are being utilized as intended, but also to identify potential gaps in reliability. Data showing that households are using stoves at lower-than-expected rates can indicate the need to investigate potential causes, such as stove breakdown, fuel supply chain gaps, and alternative financing strategies. The application of such actionable data will help steer the clean cooking sector towards more reliable solutions for women and greater emissions impact overall.