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Impacts of household energy programs on fuel consumption in Benin, Uganda, and India

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A B S T R A C T

This paper presents results of three United States Environmental Protection Agency (U.S. EPA) sponsored field studies which assessed the fuel consumption impacts of household energy programs in Benin, Uganda, and Gujarat, India. These studies expand on a previous round of U.S. EPA supported efforts to build field testing capacity and collect stove performance data in Peru, Nepal, and Maharashtra, India. Daily fuel consumption estimates of traditional and intervention technologies were made using the Kitchen Performance Test (KPT) protocol to determine the potential fuel savings associated with the respective programs. The programs in Benin and Gujarat, India resulted in significant fuel savings of approximately 29% and 61%, respectively. In Uganda, the homes using liquefied petroleum gas (LPG) consumed approximately 31% less charcoal than those not using LPG, although the total energy consumption per household was similar between the baseline and LPG user groups.

Introduction

The majority of households in developing countries depend on solid fuels as their primary cooking energy source (Bonjour et al., 2013). The pollutants from combusting solid fuels in inefficient cookstoves are estimated to be responsible for four million premature deaths per year (Lim et al., 2012) and 25% of annual black carbon emissions (Bond et al., 2013).

Growing interest and resources have been focused on finding clean and efficient stoves and fuels, which, when used in place of traditional stoves and fuels, can help mitigate these impacts (Smith, 2010). With this growing interest comes increased scrutiny that impacts attributed to cookstove programs are real and meaningful.

Given the scope of the problem and growing global interest, current, peer-reviewed estimates of fuel savings from in-home assessments are surprisingly limited (Berkeley Air, 2012). Cookstove performance is often assessed through controlled laboratory testing rather than by in-home measurements of performance, as field based assessments generally require more resources and can be logistically intensive. Controlled laboratory testing of cookstoves, while useful for technology development and standardized testing, is often not predictive of real-world performance (Berkeley Air, 2012).

To promote the collection of more field-based cookstove performance data, the United States Environmental Protection Agency (U.S. EPA) has been supporting coordinated capacity building and field study efforts. The first round of U.S. EPA funded fuel consumption studies, reported in (Johnson et al., 2013), was done with stove programs in Nepal, Peru, and Maharashtra, India. This paper, building on results from the previous projects, presents the second round of fuel consumption studies under this program focusing on a charcoal stove in Benin, an liquefied petroleum gas (LPG) program in Uganda, and a forced-draft wood stove in Gujarat, India. These projects represent a variety of potential household energy solutions whose fuel consumption impacts have not been well characterized.

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Methods

Kitchen Performance Testing

The Kitchen Performance Test (KPT) protocol used for this study is an uncontrolled, household-level test that measures real-world fuel consumption (Bailis, 2007), for which all household fuels are weighed daily for four continuous days, providing three days of fuel consumption estimates. Fuel was weighed with calibrated, digital, hand-held scales (maximum 50 kg; resolution 0.01 kg), and wood moisture was measured daily where relevant. Household fuel consumption estimates are presented as fuel mass per "standard adult" (SA) per day and fuel energy per SA per day. The SA metric is used in the KPT to normalize the caloric energy needs across gender and age with the following weights: child 0–14 years = 0.5; female over 14 years = 0.8; male 15–59 years = 1; and male over 59 years = 0.8 (FAO, 1983). The fuel consumption estimates are at a household level, which subsumes fuel use from different stoves, although each fuel type is estimated separately. In situations where multiple stoves and fuels are used to meet household energy demands, known as stove/fuel stacking (Ruiz-Mercado et al., 2011), the estimates represent the fuel use for a given fuel type regardless of whether one or many stoves were used. The technical KPT methods used here are the same as those described in Johnson et al. (2013), in which more detailed descriptions of the approach can be found.

KPT program overview

Participating cookstove programs were selected from a pool of applications sent to the U.S. EPA based on the readiness and resources of the program, location, and other factors. Berkeley Air, U.S. EPA, and Winrock International conducted an on-site training workshop in each location with staff from the selected programs as well as participants from other organizations in the country or region. The respective KPT field campaigns immediately followed the workshops. The specific projects are as follows:

Benin: The Éclair stove, developed by GIZ and locally manufactured by GIZ trained artisan producers, was the intervention technology evaluated in Benin (see Fig. 1). The charcoal burning Éclair is produced in four different designs of varying size and shape, all of which are constructed from recycled metal with secondary air holes intended to increase the thermal and combustion efficiencies by regulating airflow and more fully oxidizing the fuel carbon. The cross-sectional study took place along the southern coast of Benin in the cities of Cotonou and Porto Novo and the peri-urban community Ouidah, where charcoal is the dominant cooking fuel. Although traditional charcoal stoves were varied in this region, the Cloporte stove was predominantly used and, therefore, primarily sampled during the KPT. The Cloporte is a square or circular conical stove constructed of reclaimed metal, and comes in various sizes (see Fig. 1). A team of six university students from Cotonou surveyed 57 homes using traditional stoves and 63 homes using Éclair stoves, which were recruited by GIZ from their customer database. Participants were instructed to follow their normal stove routine during the KPT. The study took place over a two-week period during the rainy season in July 2013.

Uganda: The Ugandan project partner, Wana Energy Solutions, is a local supplier of household liquefied petroleum gas (LPG) and stoves. The KPT, which assessed the displacement of solid biofuels with cleaner burning LPG, was conducted in urban and peri-urban neighborhoods to the south of central Kampala. The stove/fuel combinations in this area were varied and usage patterns were dynamic. The most common fuels were charcoal, wood, and LPG. The study was cross-sectional, with the surveyors from Wana Energy visiting 48 homes using charcoal and LPG to satisfy daily cooking requirements, and 54 homes using primarily charcoal as the baseline comparison group. The traditional and LPG stoves are shown in Fig. 1. LPG users were identified from a list of Wana Energy customers, and the baseline charcoal users were selected from the same neighborhoods and responded that they would be able to afford LPG at the current price, helping to ensure comparability with the LPG users. The KPT was conducted during the dry season, in August 2012.

Gujarat, India: The Eco Chulha, designed and produced by Alpha Renewable Energy, Pvt. Ltd., was the intervention stove for the study in Gujurat. The Eco Chulha, shown in Fig. 1, is a forced-draft gasifier that was used primarily with wood during the KPT, although it can be used with a variety of solid biomass fuels. A total of 117 homes were sampled using a 'before-and-after' study design. Baseline measurements were carried out on traditional mud chulhas during the rainy season in early August 2013. The Eco Chulha was then disseminated and follow-up measurements were collected at the end of the rainy season in late October 2013. Two different sizes of the Eco Chulha were sampled during the study but were treated as a single group as there was no significant difference in fuel consumption performance. Homes were recruited and surveyed by members of the Self Employed Women's Association (SEWA), with the participants agreeing to pay for the Eco Chulha at a subsidized rate (Rs. 700, USD 11.29). The KPT took place in the rural Mehsana and Anand districts of Gujarat, India. SEWA hosted the project, in partnership with Alpha Renewable Energy.

Initial round of KPT studies: For context, the studies presented in Johnson et al. (2013) are briefly summarized here:

Maharashtra, India — Conducted in homes using the Oorja, a forced-air gasifier designed to burn sugarcane pellets, with the comparison groups being the users of traditional wood burning chulhas and homes using exclusively LPG.

Nepal — Conducted in homes using the Improved Biomass Stove, which is a stationary, wood burning stove made of mud and brick, with the comparison group homes using traditional wood burning chulos.

Peru — Conducted in homes using the Inkawasi stove, a built-in chimney stove constructed from adobe and either ceramic or mud bricks, which were compared to traditional open-fire stoves.

Results and discussion

Benin

Fuel consumption results for Benin are presented in Table 1, reported as mass and energy equivalent of fuel used per SA per day. Households using Éclair stoves used ~18% less charcoal per home ($p = 0.02$) and 29.5% less charcoal per SA ($p < 0.01$). These differences are based on means of the entire Éclair and baseline groups, respectively. Within each group, however, there were a variety of stove designs. The majority of traditional charcoal stoves were a version of the Cloporte, though a few alternative, metal, bucket-style stoves were also used. The Éclair designs also varied in size and shape, with four versions present in study homes. No significant differences in charcoal consumption were found between homes using different Éclair stove designs.

In addition to economic benefits for Éclair users, the charcoal savings imply substantial environmental benefits as it typically takes ~4–8 kg of wood to produce 1 kg of charcoal (FAO, 1990). Given the charcoal savings of 0.11 kg/SA/day, the use of an Éclair stove would translate into 550–830 kg of wood saved per home over the course of a year.

The 31% charcoal savings found during the KPT study are less than the 41% fuel savings derived from the Water Boiling Test 4.2.2 (WBT

Fig. 1. Traditional and intervention stoves in Benin, Uganda, and Gujarat, India.

Technical Committee, 2013) done at the local GIZ laboratory. This difference may arise from a variety of factors. For example, the cooking power demands in Benin likely differ from the evenly weighted high-power and low-power phases of the WBT, and the Éclair's performance is relatively stronger during low-power simmering. The Éclair was also not exclusively used during the KPT, and the conditions in homes were less ideal than in the laboratory. Moreover, since cooking tasks are not all equivalent to water boiling (e.g. see Fig. 11 of Dutt and Ravindranath (1993)), fuel consumption estimates from KPTs and WBTs can diverge when the local cuisine is not heavily dependent on heating water.

Uganda

The results from Uganda, as shown in Table 2, provide an indication of how LPG has been incorporated into charcoal-using households. Total energy use per SA was almost identical between the LPG and charcoal users, with the baseline households using an average of 15.2 megajoules of energy per SA per day versus 14.4 for the LPG group. Charcoal use, however, was 31% lower ($p = 0.05$) in the LPG user group, which is important, as charcoal production and its emissions have serious environmental and health impacts. For example, the charcoal savings translates into a wood savings of ~900–1400 kg per home per year assuming that it takes 4–8 kg of wood to produce 1 kg of charcoal (FAO, 1990).

The continued use of charcoal in the LPG group may be a function of economic restraints, cooking preferences, or other factors. Addressing the barriers restricting a more complete transition to LPG or finding complimentary clean solutions that further displace charcoal and wood use would help increase health and environmental benefits.

Gujarat, India

Results from India (see Table 3) are likely not illustrative of a real-world adoption scenario, but rather an idealized 100% displacement of the traditional chulha by the Eco Chulha. Due to a miscommunication, participants were instructed to use only the Eco Chulha during the time the KPT was conducted, and study homes correspondingly reported that they had exclusively used the Eco Chulha during the follow-up measurements. The instructions to only use the Eco Chulha almost certainly biased results towards overestimated fuel savings. During this idealized study scenario, significant fuel savings were observed based

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Table 1
Household fuel consumption estimates for Benin.

		N	SA/home	Charcoal (kg/SA/day)	Charcoal (MJ/SA/day)[a]
Traditional	Mean	57	3.3 ± 1.5	0.38 ± 0.25	11.4 ± 7.5
	Median		2.9	0.33	9.9
Éclair	Mean	62	3.6 ± 1.6	0.27 ± 0.14	8.1 ± 4.2
	Median		3.8	0.24	7.2
	% difference of means		10.1%	**−29.5%**	**−29.5%**
	p–value[b]		0.25	**<0.01**	**<0.01**

Statistically significant differences are printed in boldface.
± represents plus or minus one standard deviation.
[a] The net calorific value estimates used for conversion of mass to energy for wood were 19.0 MJ/kg, the accepted value used in the Water Boiling Test 4.2.2 (WBT Technical Committee, 2013), and 30.0 MJ/kg for charcoal, which was based on calorimetric tests conducted at Colorado State University of charcoal samples from Benin.
[b] Statistical significance evaluated by two-tailed, unpaired Student's t-test.

Table 3
Household fuel consumption estimates for India.

		N	SA/home	Wood (kg/SA/day)	Wood (MJ/SA/day)[a]
Traditional Chulha	Mean	117	4.0 ± 1.4	1.5 ± 0.3	27.7 ± 6.3
	Median		3.9	1.5	27.7
Eco Chulha	Mean	117	4.0 ± 1.4	0.57 ± 0.26	10.8 ± 4.9
	Median		3.9	0.55	10.4
	% difference of means		−0.04%	**−61.1%**	**−61.1%**
	p–value[b]		0.99	**<0.01**	**<0.01**

Significant differences are printed in boldface.
± represents plus or minus one standard deviation.
[a] The net calorific value estimates used for conversion of mass to energy for wood were 19.0 MJ/kg, the accepted value used in the Water Boiling Test 4.2.2 protocol (WBT Technical Committee, 2013).
[b] Statistical significance evaluated by two-tailed, paired Student's t-test.

on fuel used per SA per day (~61%, $p < 0.01$). As stove stacking has been almost universally reported in studies exploring patterns of stove adoption (Rehfuess et al., 2013), a more likely usage pattern would include both the traditional chulha and the Eco Chulha being used in a given home for various tasks.

Seasonal considerations are also important for interpreting these estimates. The baseline and follow-up field campaigns both took place during the rainy season to minimize seasonal cooking effects. The number of cooking events was similar between the baseline period (14.7 ± 5.6 SA-events/day) and the follow-up (15.1 ± 6.0 SA-events/day), although it is possible that the amount of food cooked per event differed. Both the magnitude of fuel consumption and relative fuel savings may be different during other times of year when fuel moisture content is lower, different fuels are available, and/or different foods are cooked.

The reported 100% Eco Chulha usage during the monitoring period, although likely an overestimate of what a typical stove intervention might achieve, provides an opportunity to explore potential fuel savings within a range of stove stacking scenarios. Fig. 2 shows the theoretical relationship between fuel savings and the extent to which the Eco Chulha has displaced the traditional chulha. Under more realistic stove stacking conditions, only partial displacement of the traditional technology would be achieved and actual fuel savings would lie somewhere between the baseline and the 100% adoption scenarios (represented by the solid blue line in Fig. 2). From the graph, we can estimate fuel savings based on the percentage of traditional chulha displacement. For example, if traditional chulha usage is displaced by 50%, about 0.4 kg/SA/day of wood is saved, which would be ~30% fuel savings. We have also indicated the relative amount of fuel savings that may be achieved by displacing specific cooking tasks in Fig. 2. The fuel savings per task were estimated based on data from a related study, for which fuel consumption was measured during individual cooking events on the traditional chulha and Eco Chulha. These are relatively rough estimates from a small sample size (N = 39 events), but they indicate that cooking bread and vegetables are the dominant stove use tasks and displacing the traditional chulha with the Eco Chulha for these tasks alone could result in ~50% fuel savings. Although these are only approximate estimates for the specific fuel demands of cooking tasks, they illustrate the importance of targeting the main stove use tasks for the displacement of the traditional stove.

The 61% lower fuel consumption observed during this KPT field study is slightly greater than the savings suggested by laboratory testing based on water boiling tests (WBT). Traditional Indian mud stoves have

Table 2
Household fuel consumption estimates for Uganda.

				Fuel consumption (kg/SA/day)				Fuel consumption (MJ/SA/day)[a]				
		N	SA/home	Charcoal	Wood	LPG	Kero	Charcoal	Wood	LPG	Kero	Total
Non–LPG users	Mean	54	4.2 ±2.0	0.47 ±0.3	0.07 ±0.34	–	–	14.0 ±8.9	1.3 ±6.2	–	–	15.2 ±8.9
	Median		3.6	0.44	0	–	–	13.1	0	–	–	13.6
LPG users[c]	Mean	38	4.3 ±2.4	0.32 ±0.4	0.04 ±0.12	0.092 ±0.089	0.0013 ±0.0056	9.5 ±11.2	0.72 ±2.18	4.1 ±4.0	0.052 ±0.22	14.4 ±11.0
	Median		3.2	0.23	0	0.059	0	6.8	0	2.7	0	11.4
	% difference		4%	**−31%**	−51%	**100%**	**100%**	**−31%**	−51%	**100%**	**100%**	−5%
	p–value[b]		0.7	**0.05**	0.50	na	na	**0.05**	0.5	na	na	0.7

Significant differences are printed in boldface.
± represents plus or minus one standard deviation.
[a] The net calorific value estimates used for conversion of mass to energy are the values used in the Water Boiling Test 4.2.2 (WBT Technical Committee, 2013), which for charcoal is 29.8 MJ/kg, for wood is 19.0 MJ/kg, for LPG is 44.7 MJ/kg, and for kerosene is 39.7 MJ/kg.
[b] Statistical significance evaluated by two-tailed, unpaired Student's t-test.
[c] A small group of single user households (N = 14) in the LPG group was excluded, as it consists of generally young, business professionals and there was not an equivalent demographic group in the baseline charcoal group.

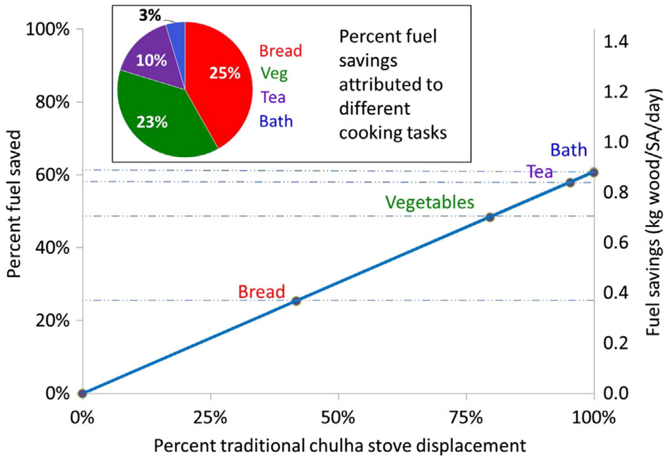

Fig. 2. Hypothetical fuel savings in homes using the Eco Chulha across a range of traditional stove displacement scenarios. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

been reported to have thermal efficiencies of ~17% (Smith et al., 2000) and the Eco Chulha was measured at ~37% (Alpha Renewable Energy Pvt. Ltd., 2012), which implies a 54% fuel savings from the WBT. This comparison is relatively coarse as the baseline stove thermal efficiencies come from measurements of Indian mud stoves from an unrelated study and may be slightly different from the traditional stoves at the Gujarat study site. There are also differences in testing protocols as the Smith et al. (2000) study used average thermal efficiency from the entire test (heating and simmering WBT phases), while the Alpha Renewable Energy tests only included thermal efficiency from the heating phase, per the Bureau of India Standards test protocol. Still, the results are comparable, and given that the Eco Chulha was reported to have been used exclusively during the KPT, the similar fuel savings estimates between laboratory and field testing appear reasonable in this case.

Comparison across projects

Fig. 3 provides a visual comparison across and within studies from both rounds of the U.S. EPA program. The fuel consumption estimates are presented on an energy basis as this provides a comparable metric for scenarios with multiple fuel types with different energy densities, as observed in Uganda and Maharashtra, India, as well as across regions or projects with different fuel types. Overall, Fig. 3 shows that, compared to using the traditional stoves, homes using the intervention stoves generally consumed less energy. In Uganda, LPG helped displace some charcoal use but the overall energy consumption was similar. In Maharashtra, India, the energy consumption was similar between homes using the Oorja as those using only LPG, though the energy consumption in both of these groups was less than half that of the chulha users.

Comparing across baseline groups, the charcoal users in Africa had by far the lowest energy consumption, which was approximately two to three times less than homes in India and Nepal, and up to four times less than households in Peru. The baseline energy use in Peru was clearly the greatest, which is consistent with the results from studies in other Latin American countries (41.8 MJ/SA/day in Mexico and 35.7 MJ/SA/day in Guatemala) (Berrueta et al., 2008; Boy et al., 2000). Much of the difference in fuel consumption between baseline users of charcoal and wood stoves, regardless of location, is likely due to the differences in thermal efficiencies between the wood and charcoal stoves. The four traditional charcoal stoves by Jetter et al. (2012), for example, had a mean high power thermal efficiency of 27%, compared to 15% for the three-stone-fire (Jetter et al., 2012). Variability in cuisine, cooking practices, and other location specific variables, such as weather and altitude, also likely contributed to the differences in baseline fuel consumption across study sites.

Conclusions and recommendations

The results presented here represent the most recent round of research done as part of the U.S. EPA's larger capacity building program in the household energy sector, complementing the KPT projects

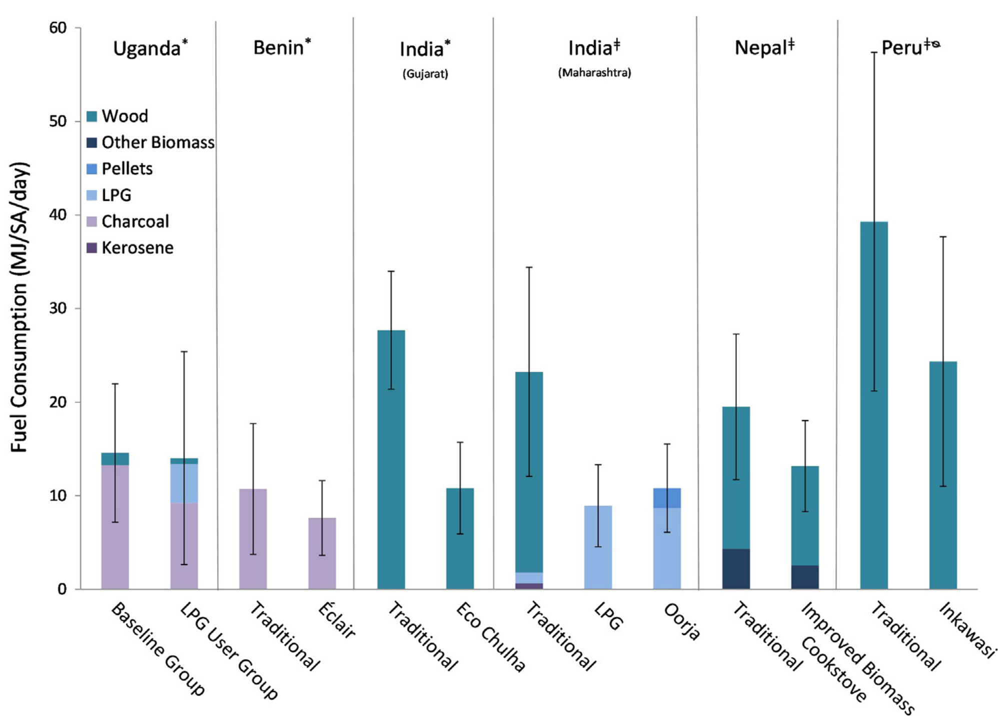

Fig. 3. Mean fuel consumption estimates in terms of fuel energy used per standard adult per day. Error bars represent ± SD. ‡Study was conducted in the first round of U.S. EPA KPT projects (Johnson et al. 2013). *Study was conducted in the second round of U.S. EPA KPT projects and results are reported in this paper. For clarity, only measurements from one of the study sites in Peru is presented (Santiago de Chuco).

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presented in Johnson et al. (2013). These studies included many promising technologies that reduced household fuel consumption in regions dependent on solid biomass fuels. The fuel consumption estimates presented here improve our understanding of how household energy programs are performing for end users and help to fill in gaps in our stove performance knowledge base. Still, further field assessments of stove programs are important to more comprehensively understand how household energy interventions are performing. Lessons and recommendations for future work are presented below:

- The success of a household energy program largely depends on sustained, correct use of its technology and/or fuel and the extent to which the traditional technology is displaced. While KPTs offer valuable real-world information on fuel consumption, they provide limited data on technology use patterns. Incorporating usage monitoring technologies as part of fuel consumption assessments would help provide a more comprehensive understanding of how technologies are being incorporated into homes, as well as indicate longer term patterns on how programs or technologies are performing.
- Characterizing which tasks are conducted using the new and traditional technologies may help guide programmatic and technology design efforts to prioritize addressing energy intensive tasks as well as finding ways to help households fully transition to clean stoves and fuels.
- Coordinated efforts between laboratory and field assessments are crucial for understanding relative performance differences, which will help in developing approaches to stove testing that more accurately predict real world performance. Current stove tests being conducted at the U.S. EPA's laboratory using the Water Boiling Test will provide performance estimates of the Éclair, Eco Chulha, and LPG stoves. Comparisons of the field data presented here with these laboratory-based estimates, and any others that become available, will help in this effort.
- A more comprehensive understanding of how household energy programs are performing could be achieved through concurrent stove emissions measurements, as these would provide important information on how programs are progressing towards health and climate goals.

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