Title

Wireless sensors linked to climate financing for globally affordable clean cooking

Journal
Nature Climate Change, 7(1)

ISSN
1758-678X

Authors
Ramanathan, Tara
Ramanathan, Nithya
Mohanty, Jeevan
et al.

Publication Date
2017

DOI
10.1038/nclimate3141

Peer reviewed

nature climate change

LETTERS

PUBLISHED ONLINE: 31 OCTOBER 2016 | DOI: 10.1038/NCLIMATE3141

Wireless sensors linked to climate financing for globally affordable clean cooking

Tara Ramanathan[1], Nithya Ramanathan[1*], Jeevan Mohanty[2], Ibrahim H. Rehman[2], Eric Graham[1] and Veerabhadran Ramanathan[3]

Three billion of the world's poorest people mostly rely on solid biomass for cooking, with major consequences to health[1] and environment[2]. We demonstrate the untapped potential of wireless sensors connected to the 'internet of things' to make clean energy solutions affordable for those at the bottom of the energy pyramid. This breakthrough approach is demonstrated by a 17-month field study with 4,038 households in India. Major findings include: self-reported data on cooking duration have little correlation with actual usage data from sensors; sensor data revealed that the distribution of high and low users varied over time, and the actual mitigation of climate pollution was only 25% of the projected mitigation; climate credits were shown to significantly incentivize the use of cleaner technologies.

Because of poverty and lack of energy access, about 40% of the world's population meet their cooking and heating needs by burning solid biomass in rudimentary stoves[2]. Particles and gases in the smoke from the stoves are major contributors to indoor and outdoor air pollution[3,4], as well as regional and global climate change[5]. The particles emitted by biomass stoves consist mainly of black carbon (BC) and organic carbon (OC)[6], 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[1]. There is an environmental impact as well. BC is a strong absorber of solar radiation and hence a climate warming agent[5]. OC consists of particles that both absorb and reflect solar radiation and has a net cooling effect[4]. Other pollutant gases in the smoke form the greenhouse gas ozone. Aside from OC, all of these pollutants lead to net warming[3–5,7,8] and are referred to as short-lived climate pollutants (SLCPs)[8], since their lifetimes (days for BC) are much shorter compared with the century or longer lifetime of CO_2 in the atmosphere. Harvesting of non-renewable biomass as a cooking fuel releases about one billion tonnes of CO_2 each year[3]. Globally, residential combustion of solid biomass for cooking contributes about 40% of BC emissions[9]; in rural India, where the present study was conducted, biomass cooking contributes as much as 50% (ref. 6).

Gas and induction stoves[2,3] are the obvious alternatives to biomass stoves, but the fuel costs[10] are prohibitive given the daily wages of the poorest three billion people[10]. Improved biomass cookstoves (ICS)[2], which still burn locally available biomass, are designed to reduce harmful emissions through more efficient fuel combustion[11–13]. Amongst these, forced-draft ICS (ICS_FD) significantly reduce emissions of CO_2, SLCPs and other particles by increasing the thermal efficiency of combustion and through near-complete combustion. However, at a capital cost of about US$70 (Methods), ICS_FD are out of reach for most of the poorest three billion[10]. Therefore, ICS_FD have typically reached homes by way of project developers at a subsidized cost. Existing carbon markets[14,15] provide credits for reductions in CO_2 to project developers who distribute or sell ICS, rather than rewarding the individuals who use ICS. Indeed, traditional verification methods do not require objective data to quantify individual usage[15]. With one exception, these markets do not permit credits for reductions of SLCPs through ICS[14], and therefore miss opportunities to incentivize adoption of ICS that mitigate both CO_2 and SLCPs. In spite of numerous national and international efforts[2,14], three billion people still rely on rudimentary, polluting stoves.

Affordability of cleaner stoves is one of the major barriers addressed in this study through a breakthrough approach, hereafter referred to as SCF for sensor-enabled climate financing, described below and further detailed in the Methods and Supplementary Methods A–H. SCF differs from traditional approaches to rural cookstove interventions in the following ways: data collected from wireless sensors are used to measure and verify daily cooking duration in each household in near real time; sensor data are converted into climate credits to pay each woman directly for her role in climate change mitigation. Rewarding users is at the heart of the proposed model and to date, we know of no other study

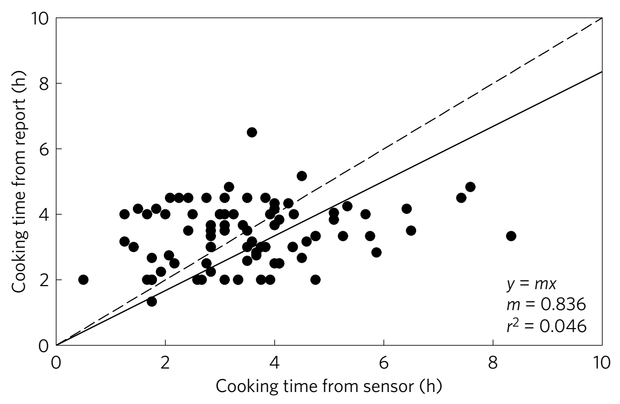

Figure 1 | Comparison of cooking duration from self-reported and sensor-reported data. Sensors were attached to traditional mud stoves, with sensors moved every 24 h to a different house in Uttar Pradesh (data collected during a previous study not described here). Eighty-eight 24-h samples were successfully collected during the six-month period. Cooking time was calculated from sensor data and compared with cooking time reported from surveys. The dashed line is the 1:1 correspondence; the solid line is the linear regression forced through zero (equation parameters inset).

[1]Nexleaf Analytics, Los Angeles, California 90064, USA. [2]The Energy Resources Institute, New Delhi 110003, India. [3]University of California at San Diego, La Jolla, California 92093, USA. *e-mail: nithya@nexleaf.org

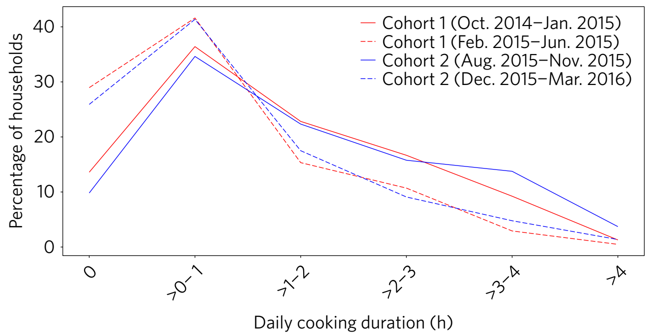

Figure 2 | Frequency distribution of household cooking duration on the ICS_FD stove in Odisha, India. Cohort 1 consists of 125 households using ICS_FD monitored by WiCS (October 2014 through June 2015). Cohort 2 consists of 331 households with WiCS (August 2015 through March 2016).

Table 1 | Projected versus actual mitigation of the programme.

	Projected	Actual
ICS_FD cooking duration (h)	380,250 h	92,289 h
SLCP mitigation (tCO_{2e})	739 tCO_{2e}	182 tCO_{2e}
CO_2 mitigation (tCO_2)	380 tCO_2	90 tCO_2
Total mitigation (tCO_{2e})	1,119 tCO_{2e}	272 tCO_{2e}

These calculations of the projected (assumes 5 h cooking per day) and actual measured mitigation of CO_2 and SLCPs are based on the 456 households from both cohorts equipped with WiCS from October 2014–March 2016 (see Methods). The mitigation is expressed in terms of tonnes CO_2 (tCO_2) for mitigation of CO_2 and in terms of tonnes CO_2 equivalent (tCO_{2e}) for mitigation of SLCPs, with the sum of the two expressed in terms of tCO_{2e}.

that utilizes individual usage to estimate climate credits for this purpose; and climate credits are given for mitigation of SLCPs in addition to CO_2. The SCF approach can be applied to increase access to other clean energy technologies provided they reduce air and climate pollution.

The main objectives of this study were to: deploy wireless sensors in a large number of households to gain unprecedented insights into usage on a mass scale; translate this usage into climate credits to pay women for the climate change mitigation they provide and make the cleanest ICS, with the largest impact on climate pollution, more affordable; increase the integrity of climate financing by verifying that only actual stove usage is rewarded; and finally understand if climate credits awarded to individual users can incentivize adoption of clean stoves.

The method used by SCF to convert individual stove usage into climate credits is described below, with full details in the Methods and in the Supplementary Information. In brief, for CO_2 mitigation we adopt the clean development mechanism (CDM) approach[14,15] and convert the non-renewable biomass fuels into CO_2 emissions. For SLCPs, we adopt the global warming potential (GWP) metric[7] to convert the climate forcing of SLCPs into equivalent CO_2 forcing. The GWP value depends strongly on the time horizon chosen to amortize the SLCP forcing. We select a 40-year horizon because more than 95% of surface cooling effects of mitigating SLCP emissions are realized within 40 years (Fig. 8.33 in ref. 7). For the combined GWP for BC, OC and ozone, this study adopts the India-specific forcing in ref. 6 to obtain a combined GWP-40 of 1,500 (Methods). This implies that the emission of a tonne of SLCPs (BC, OC and ozone) has the same warming effect as 1,500 tonnes of CO_2 over a 40-year period. The final step is to multiply the GWP of SLCPs with reductions in SLCP emissions by the ICS_FD (Methods and Supplementary Methods B) to obtain the equivalent CO_2 reduction. The total reduction is the sum of the mitigated tonnes of CO_2 and the CO_2 equivalent due to SLCP reductions and this sum is denoted by $tCO_{2e}\,yr^{-1}$. For the ICS_FD used in this study, this reduces to 0.003 tonnes CO_{2e}(tCO_{2e}) per hour of usage (Methods), translating to 5.3 $tCO_{2e}\,yr^{-1}$ assuming 350 cooking days of 5 h each. We paid each woman US$6 per tCO_{2e} mitigated. For the full use of the ICS_FD, a woman could earn about US$32 yr^{-1} enabling her to pay off the stove (US$57) in 2 years.

To assess the SCF model, we launched the Climate Credit Pilot Project (C2P2) in 4,038 homes in Odisha state, India in May 2014. Of these, 456 homes were sub-selected for deployment of the Wireless Cookstove Sensing System (WiCS) that we developed[16] to continuously monitor the duration of cooking with a resolution of minutes (Supplementary Fig. 1). Sensors were introduced in two cohorts of households: cohort 1 with 125 households in 10 villages on October 2014 and cohort 2 with 331 households in 29 villages on August 2015. Each cohort received the same training, stove model and climate credit payment rate (Methods): however, households in cohort 1 had been using the stoves for one to two months prior to sensor installation while cohort 2 had been doing so for three to ten months, a distinction that turned out to be critical to interpreting the data, as shown below. We selected a model of ICS_FD that reduced fuel consumption by 61% to 74% (Methods). The fuel reduction combined with the oxygen supply from the forced-draft fan reduces BC and OC emissions by close to 90% in the laboratory[13] with similar BC reductions measured in the field[12]. Women did not pay for the WiCS but took loans from rural banks to purchase the stoves.

Supplementary Fig. 2 demonstrates the sensors' ability to collect massive amounts of real-time data at a resolution of minutes. The majority of ICS studies[17,18] rely on self-reported data to quantify cooking duration. The value of sensor data has been recognized in recent studies[19–21] yielding valuable insights into ICS adoption. A comparison of self-reported and sensor-derived data for cooking events (the number of times the ICS was used) conducted by one of these studies[21] revealed an upward bias in self-reported data. However, cooking duration is more relevant for climate financing than cooking events. A comparison (Fig. 1) of cooking duration on traditional stoves revealed a lack of correlation between self-reported and sensor-reported cooking duration ($R^2 = 0.05$), indicating that even representative estimates of household cooking duration probably cannot be obtained from self-reported data. The WiCS automated system thus removes a major barrier regarding reliable monitoring of household-level technology adoption.

The frequency distribution of usage for both cohorts is shown in Fig. 2 for the first four months of WiCS installation and the subsequent four- to five-month period. Actual ICS usage ranged from zero to about five hours a day, with traditional stoves probably being used for any remaining cooking[18]. The frequency distribution

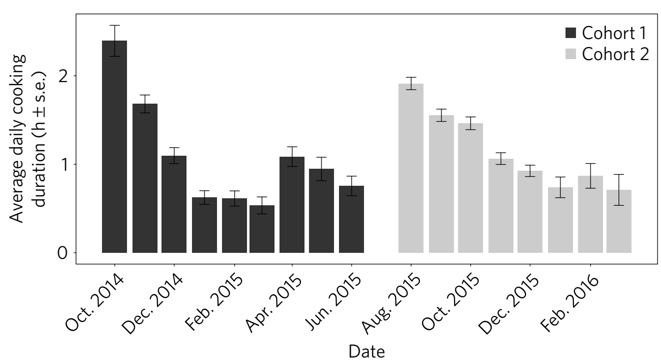

Figure 3 | Monthly trend of cooking duration during 17 months. Frequency distribution of average daily cooking duration (h d^{-1} ± s.e.) each month (black bars represent cohort 1, grey bars represent cohort 2). The standard error was computed on the per-household monthly means. The number of households included in the analysis for each month is in Supplementary Fig. 3.

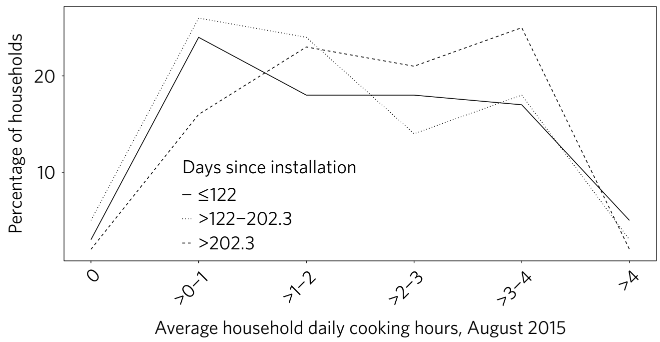

Figure 4 | Stove usage over time based on stove installation date. Stove usage data collected from the WiCS for the month of August 2015 from the 331 households monitored in cohort 2, where each line represents a different duration of stove ownership and the *y* axis represents the percentage of households with a given usage level. The number of households included in the analysis for each month is in Supplementary Fig. 4.

of daily cooking duration is strikingly similar for both cohorts during the initial 4 months after sensor installation (Fig. 2, solid lines); likewise, the decline in usage observed in the subsequent four to five months (Fig. 2, dashed lines) is also very similar across the two cohorts. Despite the dynamic nature of adoption of ICS_FD, as seen in the distinct but shifting groups of high users (>2 h), low users (<2 h) and non-users, the two cohorts behave similarly over time.

The frequency distribution shows that it would be misleading to claim one mitigation amount for all households based on potential usage of five hours for all households. We used data from the 456 households equipped with wireless sensors to verify the actual hours of usage during the intervention period of October 2014 to March 2016. We found that households used the ICS_FD for 92,289 h and not the projected 380,250 h for full ICS_FD use. Hence, the climate mitigation was only 25% of the projected mitigation (Table 1).

The incentive provided by climate credit payments is inferred from Figs 3 and 4. Initially, usage peaks during the first month after sensor installation in both cohorts (Fig. 3) in which 2 to 2.5 h is logged per day (meeting 50% of the cooking needs), but systematically drops to 1 h per day or less after 4 months (Fig. 3). Figure 4 shows that this peak after sensor installation happens across different lengths of stove ownership. In the first month following sensor installation in cohort 2 (August 2015, the month of peak usage), the frequency distribution of daily cooking duration remains strikingly similar regardless of how long (less than 122 days to more than 202 days) the women had used the stoves. Thus, the observed peak in usage in the month following sensor installation can be attributed to the promise of climate credits payments. This inference was confirmed in surveys of four focus groups representing 86 households (Supplementary Data A). Eighty per cent of respondents reported buying and initially using the stoves because of the promised climate credit payments. However, only 30% said they would buy the stove again, citing the following issues: difficulties accessing their funds due to distance from banks; low literacy; payments only once per quarter; design flaws in the ICS; and lack of available repair services. A subsequent on-site stove inspection in 36 homes (Supplementary Data B) found that 94% of stoves had issues that inhibited use, such as a damaged combustion chamber or broken fan.

The results demonstrate the potential of widespread monitoring via wireless sensors to produce unprecedented insights into energy access, science-based measurements for carbon mitigation and financing for distributed and decentralized energy access in rural areas. Results-based financing models such as SCF are relevant today, as they can provide a solid basis for understanding how best to apply the approximately US$100 billion per year of pledged climate financing from UN signatory nations that backed the 2015 Paris Agreement[22], declaring the protection of vulnerable populations in developing countries a primary goal.

Methods

Methods and any associated references are available in the online version of the paper.

Received 5 January 2016; accepted 27 September 2016; published online 31 October 2016

References

1. Lim, S. S. *et al*. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *Lancet* **380,** 2224–2260 (2013).
2. Anenberg, S. C. *et al*. Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environ. Sci. Technol.* **47,** 3944–3952 (2013).
3. Barnes, D. F., Kumar, P. & Openshaw, K. *Cleaner Hearths, Better Homes: New Stoves for India and the Developing World* (Oxford University Press The World Bank, 2012).
4. Rehman, I. H., Ahmed, T., Praveen, P. S., Kar, A. & Ramanathan, V. Black carbon emissions from biomass and fossil fuels in rural India. *Atmos. Chem. Phys.* **11,** 7289–7299 (2011).
5. Ramanathan, V. & Carmichael, G. Global and regional climate changes due to black carbon. *Nat. Geosci.* **1,** 221–227 (2008).
6. Streets, D. G., Shindell, D. T., Lu, Z. & Faluvegi, G. Radiative forcing due to major aerosol emitting sectors in China and India. *Geophys. Res. Lett.* **40,** 4409–4414 (2013).
7. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) (Cambridge Univ. Press, 2013).
8. *Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers* (UNEP and Wold Meterological Organization, 2011); http://www.unep.org/dewa/Portals/67/pdf/Black_Carbon.pdf
9. Bond, T. C. *et al*. Bounding the role of black carbon in the climate system: a scientific assessment. *J. Geophys. Res.* **118,** 5380–5552 (2013).
10. Jain, A., Choudhury, P. & Ganesan, K. *CEEW Report: Clean, Affordable and Sustainable Cooking Energy for India* (Council on Energy, Environment, and Water, 2015).
11. Patange, O. S. *et al*. Reductions in indoor black carbon concentrations from improved biomass stoves in rural India. *Environ. Sci. Technol.* **49,** 4749–4756 (2015).
12. Kar, A. *et al*. Real-time assessment of black carbon pollution in Indian households due to traditional and improved biomass cookstoves. *Environ. Sci. Technol.* **46,** 2993–3000 (2012).
13. MacCarty, N., Ogle, D., Still, D., Bond, T. C. & Roden, C. A laboratory comparison of the global warming impact of five mahor types of biomass cooking stoves. *Energy Sustain. Dev.* **12,** 56–65 (2008).
14. Freeman, O. E. & Zerriffi, H. How you count carbon matters: implications of differing cookstove carbon credit methodologies for climate and development cobenefits. *Environ. Sci. Technol.* **48,** 14112–14120 (2014).
15. Aung, T. W. *et al*. Health and climate-relevant pollutant concentrations from a carbon-finance approved cookstove intervention in rural India. *Environ. Sci. Technol.* **50,** 7228–7238 (2016).
16. Graham, E. A. *et al*. Laboratory demonstration and field verification of a Wireless Cookstove Sensing System (WiCS) for determining cooking duration and fuel consumption. *Energy Sustain. Dev.* **23,** 59–67 (2014).
17. Hanna, R., Duflo, E. & Greenstone, M. *Up in Smoke: The Influence of Household Behavior on the Long-run Impact of Improved Cooking Stoves* (National Bureau of Economic Research, 2012).
18. Lewis, J. J. & Pattanayak, S. K. Who adopts improved fuels and cookstoves? A systematic review. *Environ. Health Perspect.* **120,** 637–645 (2012).
19. Ruiz-Mercado, I., Masera, O., Zamora, H. & Smith, K. R. Adoption and sustained use of improved cookstoves. *Energy Policy* **39,** 7557–7566 (2011).
20. Pillarisetti, A. *et al*. Patterns of stove usage after introduction of an advanced cookstove: the long-term application of household sensors. *Environ. Sci. Technol.* **48,** 14525–14533 (2014).
21. Thomas, E. A., Barstow, C. K., Rosa, G., Majorin, F. & Clasen, T. Use of remotely reporting electronic sensors for assessing use of water filters and cookstoves in Rwanda. *Environ. Sci. Technol.* **47,** 13602–13610 (2013).
22. *United Nations Framework Convention on Climate Change: Adoption of the Paris Agreement* (United Nations Framework Convention on Climate Change, 2015); http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Acknowledgements

C2P2 was initiated by Project Surya, an international collaboration between University of California, San Diego, Nexleaf Analytics and The Energy and Resources Institute. The primary funding for this work was provided by L. and M. McQuown, with additional funding from Qualcomm Wireless Reach, UK DFID, Beneventures Foundation, J. and E. Frieman, and C. Kennel & E. Lehman. Project Surya was started by funding from National Science Foundation (J. Fein) and incubated at UNEP beginning 2009. We are indebted to M. Lawrence whose comments significantly enhanced the clarity of presentation. In addition we thank M. Lawrence for suggesting the field survey. We acknowledge M. Lukac for developing the WiCS. We acknowledge G. Dalai, B. Dash, M. Singh, A. Mohd, L. Singh, the staff of Saunta Gaunta Foundation and the TERI field team for stove and sensor installation, beneficiary engagement and data collection. The data for Fig. 1 were collected as part of a study led by S. Pattanayak. The focus group instrument was designed with B. Augsburg. J. Ross supported the data analysis, and E. Wu and S. Maltz helped edit the paper.

Author contributions

N.R., V.R. and I.H.R. designed the original version of this study. All authors contributed to refinement of the original design and conception of the field study. I.H.R. led the field study; J.M. and T.R. collected data in the field; and J.M. led the payments to women. T.R. and N.R. led the sensor deployment; and T.R., N.R. and E.G. conducted the data analysis. T.R., N.R. and V.R. took the lead in writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to N.R.

Competing financial interests

The authors declare no competing financial interests.

Methods

The Climate Credit Pilot Project, or C2P2 (Supplementary Fig. 5), was conducted by Project Surya (www.projectsurya.org). The core institutions of Project Surya are the University of California San Diego, The Energy and Resources Institute (TERI) in New Delhi, and Nexleaf Analytics in Los Angeles, with over a dozen collaborating institutions around the world. Surya developed the sensor-enabled climate financing (SCF) to make the cleanest improved cookstoves (ICS) affordable for the poorest three billion people.

CO_2 mitigation by improved forced-draft cookstoves (ICS_FD). The ICS_FD used by C2P2 was designed by The Energy and Resources Institute (TERI) in New Delhi. It is a top-loading, wood-burning forced-draft stove (Supplementary Fig. 6) manufactured in India and tested and certified by India Institute of Technology in New Delhi[23]. ICS_FD utilize a micro-powered fan to supply a steady source of air for more complete combustion. ICS_FD reduce climate forcing effects in three ways (data sources and calculations in Supplementary Methods B).

First, reduction in fuel consumption by increasing the thermal efficiency of the stove in turn reduces CO_2 emissions. The actual CO_2 reduction also depends on the fraction of non-renewable biomass (0.88; ref. 24) consumed. The thermal efficiency of converting biomass energy to caloric heat is 36.8% (ref. 23) for the ICS_FD used in this study compared with 10% (ref. 25) for traditional mud stoves. This should reduce fuel consumption by 74% (Supplementary Methods B), reducing daily fuel consumption to 1.8 kg d^{-1} for a household that consumes 7 kg d^{-1} on a traditional stove (calculations shown in Supplementary Methods B and derived from AMS-II G report[26]) compared with actual fuel reduction from the field, which is 61% (ref. 11). Using Government of India data[23], we multiply the reduction in non-renewable wood (0.88×5.2) with calorific value of fuel (15 MJ kg^{-1}) and the CO_2 emissions (0.0816 kg MJ^{-1}), and the mitigated CO_2 emission (for 350 cooking days) is 1.84 tonnes yr^{-1};

Second, the increase in thermal efficiency along with near-complete combustion by the fan reduces emissions of BC by 90% (refs 11–13) along with similar reductions in OC particles;

Third, reductions in CO and non-methane volatile organics emissions reduce the production of the greenhouse gas ozone.

With regards to the 90% reduction in BC documented in the field and laboratory, as discussed in the main text, it is important to note that ref. 12 evaluates two ICS_FD models: FD1 and FD2. While FD2 results in only a 2/3 reduction in BC concentrations, FD1 (which is most similar to the ICS model used in this study) results in an 85% reduction in BC concentrations. These results are similar to the 90% reduction in BC documented in the laboratory for the same stove[13].

Climate credit methodology for SLCPs. The climate credit methodology adopted in the present study estimates climate credits for mitigation of CO_2, BC, OC and ozone precursors such as CO and non-methane volatile organics (Supplementary Methods C and D). Burning of biomass also releases methane. We do not include the mitigation of methane due to lack of field data for the stove used in this study. However, this is not a major issue since methane mitigation effects are only 10% to 15% of that of the CO_2 mitigation[27].

The starting point is the radiative forcing chapter of the most recent Intergovernmental Panel on Climate Change report[7], and the United Nations Framework Convention on Climate Change (UNFCC) Clean Development Mechanism[26]. The three key components to the development of climate credits, addressed by the SCF methodology, are briefly summarized here.

First, the methodology accounts for the inclusion of short-lived climate pollutants (including cooling agents such as organic carbon). In addition to CO_2, burning of firewood leads to emissions of: BC, brown carbon and other organic aerosols; ozone precursors such as CO, methane and non-methane volatile organics; and methane (methane also has a direct greenhouse effect in addition to serving as an ozone precursor). All of the above, except 'other organic aerosols', lead to net warming. The SCF methodology explicitly accounts for the cooling effect of organic aerosols. BC, brown carbon, ozone precursors and methane are referred to as short-lived climate pollutants (SLCPs). There are two independent avenues for getting climate credits directly to the users of improved biofuel stoves. The first is the traditional approach of getting credits for mitigating CO_2 emissions through reductions in the consumption of non-renewable firewood, and by using renewable fuels instead of fossil fuels. The second avenue involves mitigation of SLCPs.

As far as possible, we adopt region (Indo-Gangetic)-specific values using field data collected by the Surya team and other published studies. We adopt the Intergovernmental Panel on Climate Change (IPCC) approach[7] for evaluating global warming potentials (GWP) for SLCPs. GWP is defined as the ratio of the time-integrated radiative forcing from a pulse release of 1 kg of a pollutant (for example, methane) relative to that of 1 kg of CO_2 (see Supplementary Methods G for the equations and steps to derive the GWP of various pollutants). GWP is a metric based on radiative properties of well-mixed greenhouse gases, measuring the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of CO_2. The GWP represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing thermal infrared radiation. The GWP metric, while originally defined for greenhouse gases, is now applied to climate effects of aerosols as well[7,9].

The second component is the time horizon that is used for translating the impact of SLCPs into CO_2 equivalents. IPCC started in the 1990s with a time horizon of 100 years. IPCC-AR5[1] uses a variety of timescales ranging from 20 years to 100 years. Several recent studies (for example, IPCC AR5 (ref. 7), UNEP-WMO[8] and refs 28,29) have shown that if current growth rates of greenhouse gases continue unabated, the warming (from pre-industrial times) can exceed 2 °C by mid-century. A primary advantage of SLCPs is that they can significantly mitigate near-term warming, thus increasing the probability for avoiding the 2 °C threshold at least in the near term. Furthermore, as shown in IPCC[7] (Fig. 8.33) the full mitigation effect of SLCPs on surface warming is realized within 40 years. On the basis of such considerations, we chose a timescale of 40 years for estimating GWPs.

Following IPCC-AR5 (ref. 7), mitigated warming effects are expressed in terms of tCO_2e, and calculated using the product of GWP for pollutant P (GWP_P)[7], and the emissions reduction for that pollutant (ER_P) when switching from the traditional stove to an improved stove:

$$tCO_2e = (ER_{BC} \times GWP_{BC}) + (ER_{OC} \times GWP_{OC}) + (ER_{ozone} \times GWP_{ozone}) \quad (1)$$

Calculations of GWP (Supplementary Tables 2 and 3) take into account the direct forcing and indirect forcing (Supplementary Table 1) due to modification of cloud albedo (a cooling effect) by OC (Supplementary Methods E and Supplementary Fig. 7). BC is directly measured in the field; therefore, the relative contributions of OC and ozone are stated in terms of BC. Using India-specific data for residential biofuel emissions of BC and OC[6], we infer the ratio of OC/BC=4 for Indian residential biofuel. We recognize, however, these ratios change from stove to stove, and when the ratio differs between the traditional baseline stove and the cleaner intervention stove, then the mass of CO_2 equivalent produced for each stove is calculated separately (as the sum of each term calculated for each pollutant P, as $mass_P \times GWP_P$), and the reduction is the difference between the respective CO_2 equivalent produced. Ref. 6 estimates that the inclusion of mitigation of ozone formation by CO, volatile organics and methane from wood burning amplifies the mitigated net warming of BC and OC by 30% for Indian residential biofuel. Equation (1) reduces to:

$$tCO_2e = [(ER_{BC} \times GWP_{BC}) + (4 \times ER_{BC} \times GWP_{OC})] \times 1.3 \quad (2)$$

$$tCO_2e = GWP_{BC,OC,ozone} \times ER_{BC} \quad (3)$$

After accounting for the lower efficacy (by about 60%) of BC, OC and ozone forcing for surface warming compared with that of CO_2 forcing (denoted GWPe), the GWP-40$e_{BC,OC,ozone}$ value estimated by C2P2 is 1,500 (range of 800–2,100) (Supplementary Methods E). As described in more detail in Supplementary Methods E, there is a significant uncertainty in the GWP values due to uncertainties in the forcing by BC and OC and uncertainty in the emissions factor reduction.

Inclusion of SLCPs expands on the existing market-based mechanism since the net warming effect of a tonne of BC, after accounting for the cooling effect of OC, is equivalent to about 1,500 tonnes of CO_2 (tCO_2)[5–9] reduced. BC and other SLCPs are super pollutants with GWPs far greater than 1 (ref. 7). This value, $GWP_{BC,OC,Ozone}$, is the sum of GWPs for BC (positive), OC (negative) and ozone (positive), each weighted by their relative emissions contribution as compared with BC, to arrive at a single number. Additionally, the GWP of 1,500 accounts for the fact that BC forcing is about 40% less effective than CO_2 forcing at warming the surface[7].

To calculate emission reduction (ER_{BC}), we take the difference in BC emissions between the traditional (Supplementary Table 4) and ICS (Supplementary Methods F) ($BC_{TRADITIONAL} - BC_{ICS}$), where BC_X is the product of the BC emission rate (kg BC per kg of fuel) for stove X, and usage of stove X as measured by WiCS. In our field data[11], it has been shown that use of the improved stove does not statistically increase overall cooking duration (Supplementary Fig. 8); therefore, we monitor only the ICS_FD, and assume it displaces an equivalent duration of cooking on the traditional stove.

For CO_2 reductions we use the methodology of the CDM[23] and Government of India data for the fraction of non-renewable biomass (88%) (see Supplementary Methods B)[26], resulting in a mitigation of 1.8 tCO_2 yr^{-1} (with full usage of ICS_FD). For SLCPs, the net reduction is essentially the difference in the emission rates for the two stoves, amounting to 2.3 kg BC yr^{-1} (see Methods and Supplementary Methods F) when women use the ICS_FD for all their cooking needs (about 5 hours per day, Supplementary Fig. 8). The tonnes of equivalent CO_2 reduction (tCO_{2e}) is the product of the 40-year $GWP_{BC,OC,O3}$ and the BC reduction, which is 3.5 tCO_{2e} yr^{-1} (1,500 × 2.3), bringing the combined (CO_2 + SLCPs) mitigated emissions to 5.3 tCO_{2e} yr^{-1}.

Selection of the cost of carbon. We adopted a conservative value of US$6 per tCO_{2e}. The price of carbon in emission trading varies widely from US$5 per tCO_{2e} (EU Emissions Trading System) to about US$12 per tCO_{2e} (California)[30], while the social cost of carbon (accounting for the climate effects) is US$36 per tCO_{2e} (ref. 30). The US$6 per tCO_{2e} enables the woman to pay off her stove in less than two years. As mentioned earlier, the ICS_FD cost US$70 and we subsidized the cost to sell the stove to each woman for US$57. With the introduction of new and improved models of ICS_FD, the cost varies from US$50 to US$70 depending on cost of power supply and other manufacturer accessories (this information is based on conversations and transactions with ICS_FD manufacturers in India).

Determining payments to individuals from stove usage. The payment to individuals is determined as follows.

On the basis of our emissions calculations, we know that by using the ICS_FD for 5 h a day, women can mitigate up to 5.3 tonnes CO_2 equivalent annually (when including reductions in CO_2 and equivalent reductions derived from SLCPs).

Using 350 days as the total number of days of cooking (adjusted for holidays and other occasions when cooking does not take place in the household):

350 (days) × 5 (hours per day) = 1,750 h of cooking per year

1 h of cooking = 5.3 tonnes/1,750 h = 0.003 tonnes h^{-1}

Women get paid according to this value on the basis of their exact cooking duration at a rate of US$6 per tCO_{2e} mitigated.

The calculations assume that any cooking on the ICS_FD displaces an equivalent duration of cooking on the traditional stove. Stove stacking[18,19], or the use of different cooking stoves to accomplish different tasks rather than completely switching to an improved stove for all cooking, could, in some instances, confound the calculations. For example, a woman may increase her total cooking duration by continuing to use her traditional stove for all cooking while also using the ICS_FD for additional cooking. This phenomenon could be measured and incorporated into calculations by monitoring in a sample of households the usage of all traditional and improved stoves in the household, and estimating the fraction by which households' mitigation should be adjusted to compensate for the increase in total cooking as a result of access to multiple stoves.

Wireless Improved Cookstove Sensor (WiCS). WiCS is an inexpensive and integrated system for the collection, transmission and analysis of cookstove temperature data that leverages wireless data transmission using a mobile phone with an attached, low-cost temperature sensor[16]. The data analysed by the WiCS server are accessed via the web-accessible visualization dashboard (Supplementary Figs 1, 9 and 10). In the laboratory, WiCS correctly identified active cooking 97% of the time and in the field, the cooking duration was not statistically different from that recorded by trained volunteers with an average difference of 0.03 ± 0.31 h (mean ± s.d.). Ref. 16 provides a more thorough discussion of the algorithm and comparison with existing methods.

Climate credit distribution. A climate fund was established at the University of California, San Diego with the support of a private donor. A bank account was opened in each woman's name to receive climate credits payments directly. On the basis of sensor data collected by Nexleaf Analytics, UCSD sent quarterly payments to TERI in India who distributed climate funds to each woman's bank account.

References

23. Ministry of New and Renewable Energy *National Biomass Cookstoves Programme* (Ministry of New and Renewable Energy, Government of India, 2016); http://mnre.gov.in/schemes/decentralized-systems/national-biomass-cookstoves-initiative
24. State of Forest Report 2011 *Socio-Economic Contribution of Forests: Production and Consumption of Forest Resources in India* 67–79 (Forest Survey of India, Ministry of Environment & Forests, 2011).
25. Venkataraman, C., Sagar, A. D., Habib, G., Lam, N. & Smith, K. R. The Indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. *Energy Sustain. Dev.* **14,** 63–72 (2010).
26. *AMS II-G Small Scale Methodology Energy Efficiency Measures in Thermal Applications of Non-Renewable Biomass* (United Nations Framework Convention on Climate Change, 2014); https://cdm.unfccc.int
27. Akagi, S. K. *et al*. Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmos. Chem. Phys.* **11,** 4039–4072 (2011).
28. Meinshausen, M. *et al*. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).
29. Ramanathan, V. & Xu, Y. The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues. *Proc. Natl Acad. Sci. USA* **107,** 8055–8062 (2010).
30. World Bank Group *State and Trends of Carbon Pricing* (2014); http://www.worldbank.org/content/dam/Worldbank/document/Climate/State-and-Trend-Report-2015.pdf