nature sustainability

Analysis

https://doi.org/10.1038/s41893-022-01039-8

A geospatial approach to understanding clean cooking challenges in sub-Saharan Africa

Received: 12 May 2022

Accepted: 1 December 2022

Babak Khavari[1], **Camilo Ramirez**[1], **Marc Jeuland**[2] & **Francesco Fuso Nerini**[1,3]

Universal clean cooking is a key target under Sustainable Development Goal (SDG) 7, with implications for several other SDGs, such as good health, gender equality and climate. Yet, 2.4 billion people globally still lack access to clean cooking. The situation is especially dire in sub-Saharan Africa (SSA), where only 17% use clean options. We develop OnStove, an open-source spatial tool comparing the relative potential of different cookstoves on the basis of their costs and benefits, and apply it to SSA. Our results suggest a severe market failure as the currently most used solution, traditional biomass, produces the lowest social net-benefits nearly everywhere in SSA. Correcting this failure, which stems from multiple market and behavioural obstacles, would deliver significant health, time and emission benefits but requires identification and promotion of policies to transform cooking energy use. Spatial mapping offers a more nuanced understanding of the costs needed to deliver cleaner cooking transitions than was previously possible, which is useful for improved targeting of intervention strategies.

Clean cooking is commonly defined as cooking with fuels and stove combinations that meet the standards set by the World Health Organization's Guidelines for Indoor Air Quality[1]. As of 2020, roughly 2.4 billion people worldwide lacked access to clean cooking, relying on polluting fuels instead to meet their daily cooking needs[2]. The lack of clean cooking is especially pronounced in sub-Saharan Africa (SSA), where only 17% of the population currently use clean solutions. Furthermore, between 2000 and 2020, the number of people without access to clean cooking increased by almost 50% in the region, as population growth outpaced the increase in access[2]. The use of polluting fuels is estimated to cause approximately 3.2 million premature deaths annually and impede progress on gender equality and environmental quality goals[2]. Due to the widespread negative impacts of polluting cooking fuels, universal access to clean cooking was incorporated as one of the targets of the Sustainable Development Goals (part of SDG target 7.1)[3]. This target has been shown to be directly linked to the achievement of many other SDG targets as well[4].

The slow transition to clean cooking has received ample attention in the literature, and much work highlights the wide variation in the pace and outcomes of this transition across regions[3,5–7]. A vast and expanding literature highlights the barriers inhibiting wider uptake of clean cooking technology, such as underdeveloped supply networks[8,9], the need for other energy services offered by traditional fuels (for example, heating)[9] and affordability constraints[10,11], among others, as well as discrepancies, often gendered, between the benefits that decision-makers perceive and the benefits experienced by households[12]. Many of these factors vary considerably with geography and as a function of community and household characteristics. Thus, Geographic Information Systems (GIS) can help increase understanding of how fuel availability, access to infrastructure and relative fuel prices change across locations, and can inform better planning.

---

[1]Division of Energy Systems, KTH Royal Institute of Technology, Stockholm, Sweden. [2]Sanford School of Public Policy, and Duke Global Health Institute, Duke University, Durham, NC, USA. [3]KTH Climate Action Centre, KTH Royal Institute of Technology, Stockholm, Sweden. e-mail: khavari@kth.se; camilorg@kth.se; ffn@kth.se

For policymakers in SSA, the use of GIS can help clarify where transitions to improved technology are currently lagging most, relative to their potentials, and can facilitate prioritization of policy and investment support. While GIS tools have been widely used to support electricity access planning[13,14] and to assess the suitability of specific cooking fuels[9,15], they have not been applied to systematically assess and compare the relative value, measured as net benefits, of improved cooking alternatives.

Here we estimate and describe the costs and benefits of implementing universal clean cooking in SSA. To this end, we develop and apply an open-source, scalable and reproducible spatial tool comparing the relative potentials of different cooking solutions (OnStove). OnStove is a raster-based tool determining the net-benefit value of different stoves for every grid cell of a given region. The tool accounts for four key benefits: reduced morbidity, mortality, emissions and time saved, as well as three costs: capital, fuel, and operation and maintenance (O&M). The fuel–stove alternative providing the highest net-benefit is identified for each grid cell (see Methods for detailed descriptions of each benefit and cost). The tool also gives users the ability to omit specific categories of benefits and costs, enabling assessment of net benefits from different perspectives (for example, social or private net-benefit).

OnStove's inputs are divided into three categories: GIS datasets, socio-economic and techno-economic specifications (Fig. 1). GIS datasets are used to capture the aspects of an area of interest (AOI) that vary over space, such as costs and time spent collecting fuels. The geographic approach provides insight on factors that may especially hinder or catalyse the adoption of clean cooking in particular locations, such as economic opportunity, fuel availability or lack of technology-specific infrastructure (for example, no access to electricity). The Supplementary Information provides a list of the GIS datasets used in the analysis and their purpose (including information on their level of spatial aggregation), as well as details on the stove-specific and other input assumptions.

In this first application of OnStove, we compare nine stove types split in three categories: traditional (biomass and charcoal), improved cookstoves (hereafter ICS, this category includes natural and forced draft biomass as well as forced draft pellets and charcoal) and clean (electric, LPG and biogas). We summarize insights from this spatial analysis emerging from two distinct perspectives, one social and one private. The social perspective accounts for all private net-benefits: net stove and fuel costs, health costs avoided and the value of time saved, plus externalities such as greenhouse gas (GHG) emissions and health spillovers avoided. It applies a social discount rate (or social marginal rate of time preference, where the discount rate describes the rate at which money loses value over time) of 3% to weigh costs and benefits over time. The private scenario accounts only for the reduced morbidity, mortality and time spent collecting fuels and cooking experienced by households that adopt new cooking technology. This scenario applies a discount rate of 15%, which is more consistent with individuals' private rates of time preference. Uncertainty regarding the specific value of the many model inputs across SSA is substantial and may influence the results. An additional analysis that varied 33 input parameters using 680 scenario combinations sheds light on the importance of these uncertainties and is provided in the Supplementary Information. Drawing on the model results and on relevant related literature, we also discuss the technical and political options that could help to speed up achievement of universal access to clean cooking, and highlight the analytical needs related to better evaluate the appropriateness of such options.

A severe market failure

Our results point to the important role of market and behavioural obstacles in the current choice and distribution of cooking technologies in SSA. Most people in the region still rely on traditional stoves for cooking, as private benefits and externalities connected to stove switching (for example, many of their health effects, the value of time saved and environmental damages) do not appear to be properly quantified, understood or internalized. Results indicate that the social optimum based on current infrastructure (with optimal referring to the stoves with the highest net-benefit) corresponds to a cooking energy situation with 765 million people primarily using LPG stoves, 350 million cooking with electricity, 19 million using biogas and about 160,000 using improved biomass cookstoves (biomass forced draft ICS) (Fig. 2a). The OnStove social cost-benefit analysis shows that traditional biomass and charcoal stoves would not deliver the highest net-benefit anywhere in the region. This is in stark contrast with the current situation in SSA, where 83% of the population relies primarily on traditional stoves[2]. This indicates the extreme disconnect between the stove options that are ideal for social well-being and those that people are actually using.

Even when accounting only for private benefits, health (without spillovers) and time, results continue to show a large disconnect between current decisions and optimal outcomes (Fig. 2b). Thus, markets on their own do not appear to be delivering solutions that would benefit many people. According to this private-benefits analysis, most people in the region (~80%) should use clean cooking solutions (Fig. 2b) simply for the private benefits that these technologies deliver. The remaining 20% would use transitional stoves such as charcoal ICS or biomass ICS. As in the social analysis, LPG is the most prevalent technology in the stove mix (for about 851 million people), followed by charcoal ICS (190 million), electricity (45 million), improved biomass cookstoves (37 million, three quarters using forced draft and the rest natural draft) and finally biogas (12 million) (Fig. 2b). The larger presence of transitional stoves in the private scenario highlights the reality that not all households will benefit the most from switching to fully clean solutions. Factors that lead to lower benefits of clean alternatives include a low value of time (that is, reflected in low wages and (or) unequal distribution of wealth) and low value of statistical life (VSL), which is tied to income level. Nonetheless, many households in SSA would still appear to benefit privately from using improved or clean technology and yet are primarily reliant on traditional cookstoves today. The fact that these households do not adopt clean alternatives is clear evidence that other barriers, which we discuss in more detail below, remain determinant.

ICS as transitional solutions

We analyse four ICS options (forced and natural draft biomass, pellets and charcoal) that have been classified as 'improved' or transitional[1]. ICS have lower benefits than clean stoves in terms of health, emissions avoided and time saved but are nonetheless more efficient than their traditional counterparts. Furthermore, their costs are typically lower than those of clean stoves and their operation tends to be similar to that of traditional stoves, which limits the learning effort needed for their use[5]. These factors contribute to ICS potentially playing an important role as transitional solutions on the path to more widespread use of clean options.

Cost advantages notwithstanding, in the optimal social benefits scenario (Fig. 2a), ICS (all biomass forced draft) would only be used in the Democratic Republic of Congo, Mali, Niger and Chad by ~160,000 people. Their low share is partly because biomass harvesting in SSA is unsustainable in many locations, such that these stoves result in higher net emissions than cleaner alternatives. Charcoal ICS is, however, prevalent in the private benefits scenario (Fig. 2b). This is because charcoal production is a particularly emission-intensive process[16,17] and reduction of emissions is the largest category of benefits (or for charcoal, costs) omitted from the private net-benefit equation. In general, charcoal ICS is privately optimal in countries with lower VSLs (that is, where health benefits are valued less). Similarly, the prevalence of biomass ICS in the optimal stove mix increases in the private scenario. Three countries: Burundi, Eritrea and Malawi, have a majority of their

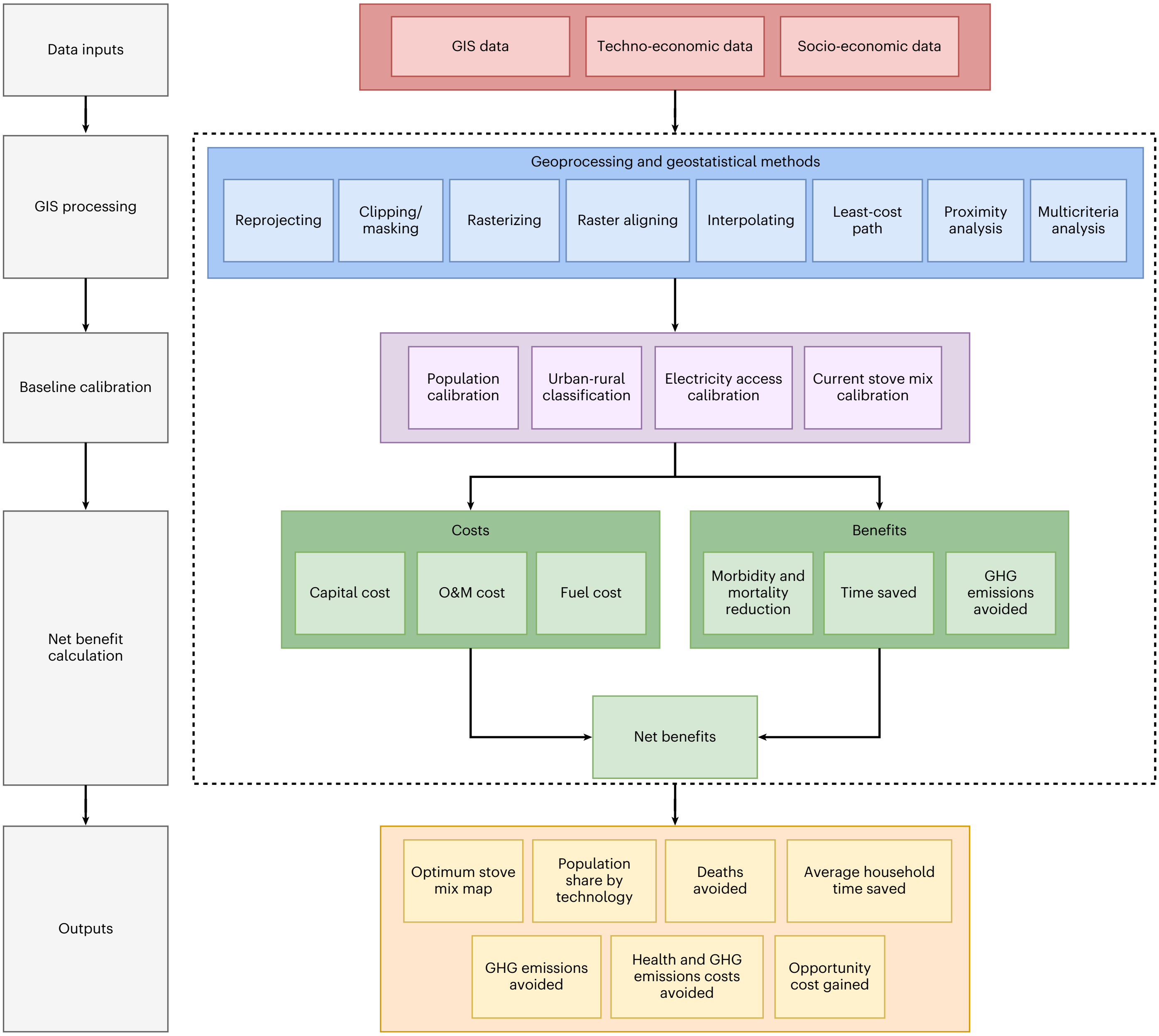


Fig. 1 | Simplified OnStove schematic describing the input data, processes and outputs. The input data and processes are described in text as well as in the Supplementary Information. The processes included within the dashed lines (that is, GIS processing, baseline calibration and net-benefit calculations) constitute the core components of OnStove.

population benefiting the most from biomass forced or natural draft ICS (80, 73 and 82%, respectively). In Burundi, this is because the VSL (used to value mortality benefits of cleaner alternatives) and the minimum wage rate (used to value time) is very low. In Eritrea and Malawi, in contrast, relatively low fuel collection times reduce the time costs associated with use of biomass ICS.

Overall, these results clearly show that considering a restricted set of benefits, or applying lower valuations to them, tends to make cheaper ICS technologies more attractive. They also help to highlight factors that relate to the behavioural obstacles impeding cleaner cooking adoption. For example, time savings and health benefits may not always be salient to households and particularly among household decision-makers. These individuals—typically male heads of households—are rarely the same people who bear the majority of the burdens of fuel collection and exposure to pollution from combustion in the kitchen environment, these people tending to be women[18]. This disconnect is thus the source of potential household 'internalities' (that is, inefficiencies arising from intra-household preferences that are undervalued due to bargaining power asymmetries).

Multipronged interventions needed

Markets alone are failing dramatically in delivering on the promise of clean cooking. Achieving enhanced alignment between household cooking technology use and the socially, or even privately, optimal technology use will thus require more than simple tweaking of markets. Rather, concerted and coordinated policy action that simultaneously tackles multiple barriers and obstacles appears necessary[8]. In the optimal social benefits scenario, virtually everyone in SSA would use clean cooking solutions, with LPG as the most prevalent option (for 67% of the population), followed by electric stoves (31%). The latter share of

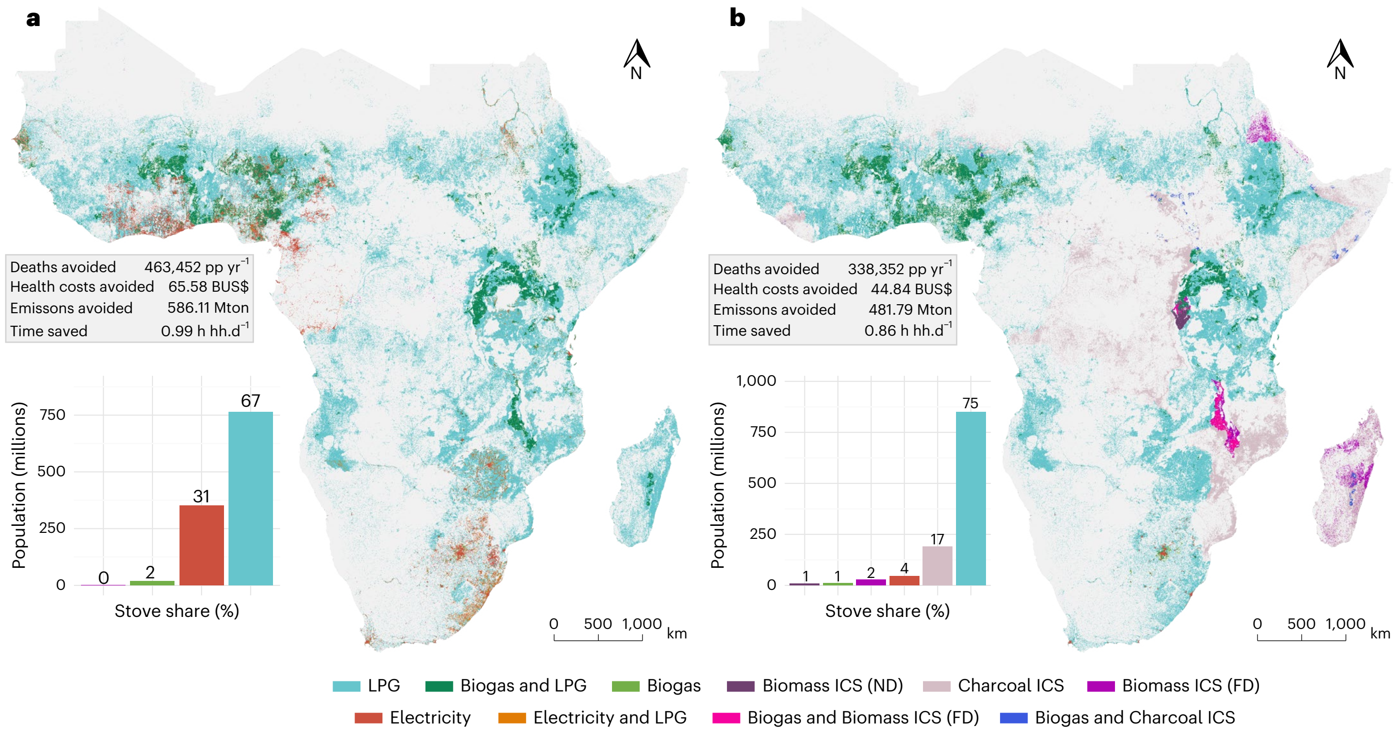


Fig. 2 | Spatial distribution of the stoves with the highest net-benefits across SSA, together with barplots of population shares of each stove. a, A social net-benefits perspective including both private benefits and externalities. **b**, A private net-benefits perspective, excluding externalities. Each panel also includes summary statistics for deaths avoided, health costs avoided, emissions avoided and time saved as derived from switching stoves. ND stands for natural draft and FD for forced draft stoves. Results have been produced with the OnStove model at a spatial resolution of 1 km^2.

electric cooking is significant as only about 48% of the population in SSA have access to electricity[2], and OnStove does not account for future increases in this percentage. From a social net-benefits perspective, electricity is most often preferred when available (Fig. 3a). Thus, integrated planning efforts of expanded access to electricity and clean cooking would probably substantially increase the optimal share of electric cooking.

In the scenario maximizing private benefits, LPG stoves become even more competitive. This is largely due to the lack of accounting for GHG emissions, where electricity has a relative advantage given the share of renewable power generation in SSA (Fig. 3b). Simultaneously, the total share of clean stoves decreases, compared with the social benefits scenario, as charcoal ICS becomes privately attractive in a number of locations. Thus, omission of social benefits (that is, spillover effects from kitchen emissions, avoided GHG emissions and the costs of illness borne by the public health system) renders the benefits of adopting clean stoves too small to offset their higher costs for a sizeable share of the population.

As previously noted, household cooking technology choices in SSA at this time are highly divergent even from the privately optimal technology mix. This is probably due to underdeveloped supply chains for improved technology[8], household internalities (that is, a misalignment of decision-makers' preferences and benefits to household members)[12], liquidity constraints that inhibit adoption of new solutions[10,11], and cultural or peer influences whereby people mimic the costly behaviours of others around them[19]. Other key behavioural challenges that can influence the household decision calculus include present or short-term bias, a lack of salience for non-pecuniary benefits[10,11] and fuel stacking (the use of several fuel–stove combinations)[20–22]. Addressing this complex web of factors and barriers will require coordinated policies, interventions, and cooperation between governments and private sector suppliers of clean solutions[8].

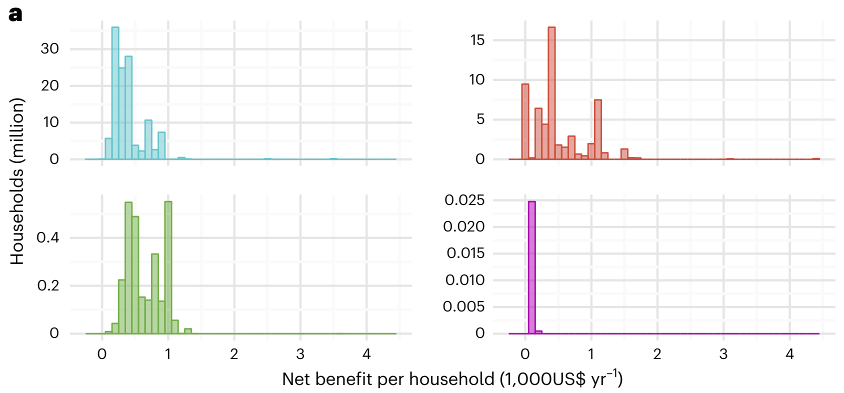
The presence of large externalities further contributes to this market failure; achieving the social optimum in their presence requires either (1) subsidies to reduce the private user costs of clean technology, (2) taxes to raise the private user costs of polluting solutions or (3) command-and-control regulations that limit choices. These potential interventions have varying advantages and disadvantages. The latter two policies, for example, would be hard to implement for traditional stoves and fuels that are rarely purchased. As such, the first approach is recommended, although we admit that subsidies are unlikely to be sufficient on their own, given the behavioural obstacles and household internalities previously mentioned, and owing to high subsidy costs and potential leakage. Other actions needed include information provision, social marketing that targets influential sub-groups, empowerment of marginalized populations (particularly women), and supply chain and market strengthening.

The urgent case for policy action

Traditional stoves have many disadvantages. People relying on biomass fuels often spend considerable time on fuel collection and preparation of food. For example, it is estimated that rural household members using traditional stoves, often women and children, spend approximately 1.3 hours daily on fuel collection[23]. Furthermore, much of the biomass collection is unsustainable, contributing to forest degradation and increased GHG emissions[17]. Finally, around 700,000 deaths in Africa in 2019 were attributable to household air pollution (HAP)[24]. OnStove captures these negative consequences by monetizing the benefits of time saved, avoided emissions, and reduced morbidity and mortality from transitions to cleaner options.

When socially optimal technology is used, the impacts of adopting the technologies with the highest net-benefits in SSA include 463,000 averted deaths per year and reductions in health costs of US$66 billion (Fig. 2a). This decrease in deaths and health costs results from a major

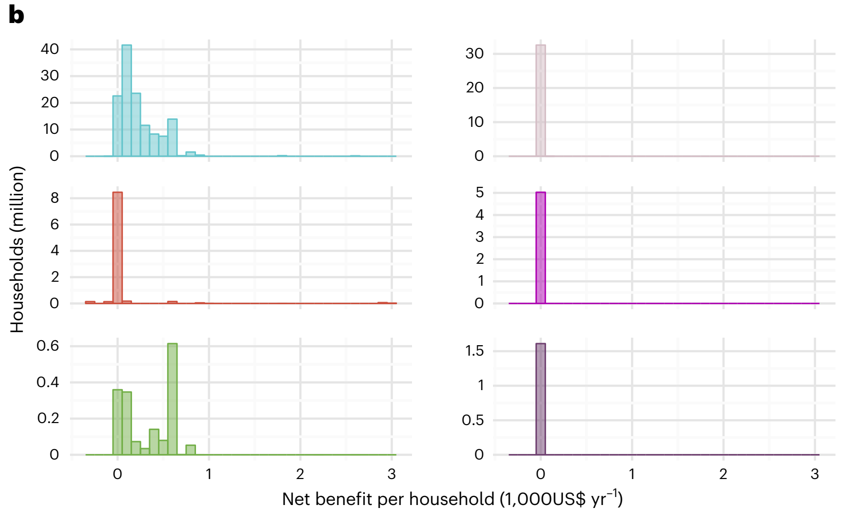
a



					IQR		*n*
Min	Max	Mean	Median	s.d.	Q1	Q3	(M.hh)
−18	351	39	32	26	22	42	122.47
−0.7	440	51	44	44	24	67	56.58
3	359	66	57	27	44	91	2.70
12	16	13	13	0.6	13	13	0.03

All values are presented in US$ yr^{-1} per household except for *n* presented in million households.

b



					IQR		*n*
Min	Max	Mean	Median	s.d.	Q1	Q3	(M.hh)
−151	2,626	225	156	230	63	347	131.66
−23	57	12	12	9	5	18	32.58
−349	2,963	−4	−47	315	−47	−47	9.20
−14	1	−5	−5	3	−5	−4	5.03
−14	2,624	352	371	267	84	626	1.70
−13	−13	−13	−13	0.03	−13	−13	1.61

All values are presented in US$ yr^{-1} per household except for *n* presented in million households.

Fig. 3 | Distribution of the net benefits per household across SSA as obtained by switching to the highest net-benefit stove mix. a, A social net-benefits perspective including both private benefits and externalities. **b**, A private net-benefits perspective, excluding externalities. ND stands for natural draft and FD for forced draft stoves. The plots show the net-benefit per household in 1,000 US$ yr^{-1} and the tables show the minimum, maximum, mean, median, s.d. and the interquartile range (IQR) (quartiles 1 and 3) of the net-benefit value in US$ yr^{-1} across the households. Moreover, sample sizes (*n*) are shown in million households. The ranges and variability of the distributions are highly dependent on spatial factors such as relative wealth and proximity to electricity infrastructure, urban centres and (or) forest cover among the households using each technology. The differences in the distributions of the social and private perspectives are mainly driven by the absence of externalities in the latter. The presence of negative net-benefits is explained by OnStove choosing to switch only when net-benefits provide a benefit gain (positive benefits). This constraint avoids recommending stove switching driven by lower costs at the expense of lower benefits.

shifting towards LPG and electric stoves, which dramatically reduce exposures to harmful emissions. Even with privately optimal technology (excluding externalities), the number of deaths and health costs avoided would sum up to 338,000 and US$45 billion, respectively (Fig. 2b). This is a significant improvement from the current situation but is considerably lower than that under the social perspective, as transitional options appear privately optimal in more locations of SSA.

The total time saved in the social perspective averages to about an hour per household per day. This is slightly higher than in the private perspective (Fig. 2) owing to the greater presence of electric cookstoves in the social perspective, and the fact that these technologies have the lowest cooking times[25]. Fuels requiring substantial collection time (biomass and biogas) are not widely used in either scenario. It is important to highlight that these overall time savings do not account for changes such as cooks' ability to engage in multiple activities when using advanced technologies. Similarly, the emissions avoided are highest in the social scenario, at about 586 million tonnes of CO_2-eq (Fig. 2a), compared with 482 million tonnes of CO_2-eq in the private scenario (Fig. 2b). Although such emissions reductions are not valued in the latter, households shifting to more efficient technology on the basis of their greater private net-benefits would nonetheless generate fewer emissions.

In conclusion, both perspectives suggest that considerable benefits—health improvements, emissions reductions and lower time spent on collecting fuels and cooking food—would result from a shift to more efficient technologies, and these benefits well outweigh these options' stove and fuel costs. In the social benefits scenario, the benefits are higher across all categories because the technologies favoured are cleaner and more efficient.

The costs of cleaner fuels and stoves

The net capital investment required to attain the highest social and private net-benefits would reach US$7.5 billion (Fig. 4a) and US$3 billion (Fig. 4b) per year, respectively. These costs include the cost of new stoves, the grid capacity upgrades needed to sustain electrical cooking, as well as the fuel cylinders needed to scale-up LPG usage. This can be contrasted to the annual investments needed to reach universal residential electrification, estimated at US$41 billion[2]. When comparing these investment numbers, it is important to note that some of the costs accounted for in these scenarios (especially grid capacity upgrades)

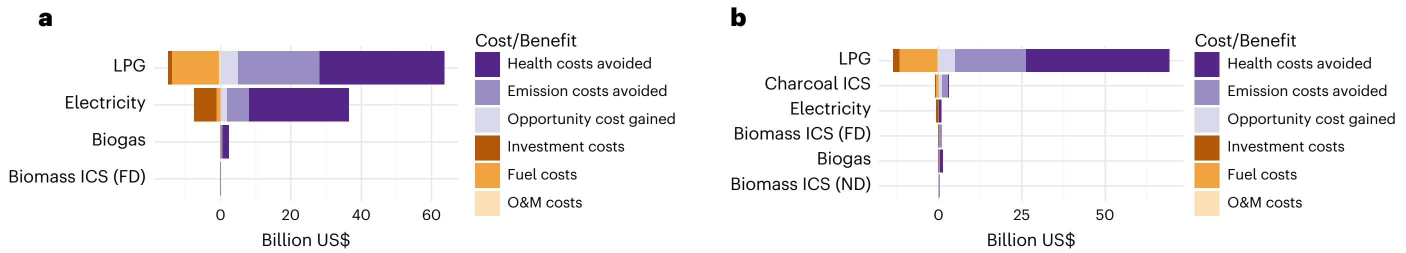


Fig. 4 | Total levelized costs and monetized benefits for each optimal stove type. a, A social net-benefits perspective including both private benefits and externalities. **b**, A private net-benefits perspective, excluding externalities. All costs and monetized benefits are relative to the current fuels and stoves used in SSA, hence the values shown represent the total extra costs and monetized benefits throughout SSA as derived from switching to the optimal stove mix under each perspective. ND stands for natural draft and FD for forced draft stoves.

would deliver non-cooking benefits to households. Indeed, previous research has shown that investment towards SDG target 7.1.1 (universal electricity access) can also be viewed as investment towards SDG target 7.1.2 (universal access to clean cooking) and vice versa[26–28].

Distinct from capital costs, the largest share of costs included in the model comes from the purchase of commercial cooking fuels (electricity, LPG or charcoal). The annual fuel costs for the technology mix selected under the optimal social benefits framing amount to US$14.4 billion (Fig. 4a), and these decrease to approximately US$12 billion for the privately optimal technology mix (Fig. 4b). Here it is important to remember that all costs (and benefits) are relative to the current stove situation. Therefore, if the solution with the highest net-benefit in a given cell has lower fuel costs than the current technology, these fuel costs will be negative. This situation pertains to cells where biomass ICS and biogas are adopted, and in some countries and grid cells, also for charcoal ICS and electric stoves. Biomass ICS and biogas in particular do not require fuel purchases. For charcoal ICS, cost savings are seen where traditional charcoal is currently dominant, as the use of more efficient ICS stoves entails fuel savings. Finally, for electricity, cost savings occur in countries where electricity costs are especially low, such that electric cooking generates savings relative to continued use of currently purchased fuels (especially LPG).

While the cost of achieving universal clean cooking is comparatively low, low cost is neither the same as affordability nor does it determine likelihood of use[29]. Indeed, factors such as households' variable and uncertain income patterns and non-discretionary expenses, difficulties in fuel procurement, as well as stacking behaviour and preferences, also need to be addressed to achieve widespread adoption and long-term use of clean technologies[30]. Data regarding these factors are often unavailable. To assess affordability, we present, in the Supplementary Information, cost-only maps for each privately and socially optimal technology, as well as an affordability ratio (defined as the ratio between the location-specific total levelized cost of cooking per household and the minimum wage). The cost maps highlight the problem that can arise from neglecting household time preferences. This is especially true when higher discount rates are used (that is, in the private perspective), as the total relative levelized costs per household are substantially higher than with a lower discount rate (that is, in the social perspective). Moreover, this affordability perspective reveals that only about 25% of households rank below a 4% affordability ratio in the private perspective, and only about 10% of households rank below a 4% affordability ratio in the social perspective (the lower the ratio the better). This demonstrates the high cost of cleaner cooking solutions for poor households, and the urgency and challenge of addressing affordability.

Ways forward to universal access to clean cooking in SSA

The divergence between the private and social benefits of clean cooking, globally and in SSA, has been identified in previous studies as a major policy challenge that requires concerted policy actions to address[5,6,12,31]. Previous work has also highlighted the substantial heterogeneity in outcomes that arises from different assumptions, based on empirical data, about the values of parameters that influence the costs and benefits of cooking technologies[32]. However, neither the spatial patterns of this divergence nor the implications for targeted policies and interventions have previously been characterized. Here we present OnStove—a spatially explicit clean cooking transition tool using a cost-benefit approach applied to SSA. Critically, the approach allows us to conclude that the economic rationale for strong policy action to supply clean cooking technology at low cost applies across this entire region.

Indeed, a majority of people in SSA currently use traditional biomass for cooking, but the socially optimal technologies across most grid cells in the analysis are clean stoves. Internalizing only private benefits, including non-monetary aspects related to health burdens and time losses, suggests some role for charcoal and biomass ICS cooking, but no traditional stoves. The fact that existing technology use in SSA is so different from this private optimum highlights the scope of the challenge and the fact that markets and current policies are failing to provide the technologies that would benefit many millions of people in the region.

Transitional technologies, which appear to be privately optimal in some locations, still impose substantial health and environmental consequences relative to the cleanest technologies, that is, biogas, LPG and electric cooking. A different perspective that includes the full social benefits almost completely removes transitional stoves from the set of optimal technologies. Thus, interventions are urgently needed to overcome current impediments to adoption. The challenge is especially great in locations with low wages, severe wealth inequalities (and hence low health and time valuations) and lacking infrastructure such as effective LPG distribution networks and electricity connections. Here it is also worth noting that technologies deemed optimal on average within a grid cell may not be optimal for all households living in that location due to within-cell heterogeneity that further emphasizes the importance of effective targeting.

The multifaceted interventions that are required are largely structural and would clearly require resources, which have not been fully included in this analysis. As such, the framing here provides an upper bound on the private and social net-benefits of technology adoption, which is nonetheless useful for several reasons. First, the metric of social net-benefits that is derived is most easily interpreted in this way. Specifically, that metric indicates the maximum cost that could be incurred to support a cooking energy transition while still leaving the beneficiary population no worse off. This is a valuable metric because it equips decision-makers (governments and donors especially) with information that they can use to assess the rationale for different potential policy packages, given their expectations regarding the impacts of those policies. Second, it avoids obscuring the results with assumptions about both the effectiveness and costs of different policy interventions, which are probably spatially heterogeneous. This is important because the evidence base on both costs and effectiveness is extremely limited, and certainly does not currently support a spatial differentiation.

Indeed, the set of interventions that appear necessary are many and diverse. Subsidies have already been discussed, but financing would also help to loosen affordability constraints and encourage households to experiment with new technology. Our results indicate that most households in SSA would struggle to afford cleaner cooking alternatives. Education and decent employment options that raise the opportunity cost of time could raise the value of time spent cooking and incentivize efficient technology adoption. Individuals who see economic gains in finding work relative to the money saved from collecting fuels from the environment or using cheap but inefficient cooking technologies would more readily transition. Here, household internalities resulting from gender norms and lack of women empowerment and work opportunities must also be addressed. This could increase households' health valuations, which are highly correlated with economic status[33]. Private and public health costs can furthermore be made more salient through awareness-raising interventions that draw attention to the health effects of traditional cooking. Fully in the sphere of spillovers, there is a need to incentivize more sustainable harvesting of biomass using climate mitigation incentives.

Beyond these aspects, there is also a need for investment in complementary infrastructure and supply chains for clean cooking solutions. In electrified locations, for example, electric cooking was shown to be the most often preferred clean cooking technology from a social benefits perspective. Meanwhile, investments in cylinders, storage capacity, filling plants, road network improvement and expansions, and road and rail transport tankers are needed to scale-up the adoption of LPG[34]. The significant investment requirements to support such solutions make it imperative for energy planners to account for energy-for-cooking needs while developing their energy systems. The use of a spatially explicit model such as OnStove can aid in these developments by providing insights on how cooking technologies should be scaled-up to provide universal access to clean cooking solutions.

Methods

To assess the benefits and costs of clean cooking in different parts of SSA, we developed OnStove, an open-source geospatial tool for determining the net benefits of different cooking solutions in every km^2 of a given study area. The tool uses state-of-the-art geoprocessing methods to process raw geospatial data and produce cost-benefit analysis results. OnStove takes into account the benefits with regards to reduced morbidity, mortality, carbon emissions and time spent cooking, as well as costs related to capital, fuel and O&M. The stove with the highest net-benefit (combined benefits minus combined costs) in each km^2 is selected. The tool is highly modular and enables easy exclusion or inclusion of existing or alternative cooking technologies.

Inputs

OnStove's inputs are divided into GIS datasets, and socio- and techno-economic specifications. GIS datasets capture spatial aspects of the AOI (note that our analysis is run on a national basis; AOI refers to a specific country). The socio-economic data provide information related to the socio-economic situation of the AOI. The techno-economic data then contain information about the stove technology options. See the Supplementary Information for a list of the GIS datasets used in the analysis, as well as the data entered in the socio- and techno-economic files.

Baseline

To calculate the net benefits of different stoves relative to the existing situation, it is important to first specify which stoves are currently used across the AOI (in the baseline). We disaggregate the current stove shares between urban and rural areas of the AOI using estimates on this split for the year 2020 in each country[35]. We next determine who could potentially cook with electricity by estimating the electricity access rate in the different cells of the AOI. The calibration of electrified people is done in OnStove using three different spatial datasets: population, nighttime lights and medium-voltage lines (the Supplementary Information includes more information on these datasets). The calibration is a multicriteria analysis that uses the three datasets and weights to rank the importance of each to match the electrified population of the AOI with the total current electrification rates in urban and rural areas. The cells of the AOI are calibrated to be either fully electrified, partially electrified or non-electrified. The Supplementary Information outlines the baseline values of stove shares and electrification rates used in different countries.

Net-benefit calculations

To determine which stove should be used in each cell to maximize net benefits, we used a modified version of the net-benefit equation presented in ref. 5. In that approach, the net benefits of a cooking technology transition are calculated as the difference between the total benefits and total costs resulting from switching stoves (equation 1):

$$\text{Net benefit} = \text{Benefits} - \text{Costs} \tag{1}$$

The stove with the highest net-benefit is chosen as the stove to use in each cell, as long as the benefit is positive (that is, we avoid choosing a stove due to its lower costs at the expense of lower benefits). The benefits are defined using equation (2):

$$\text{Benefits} = (\text{Morb} + \text{Mort} + \text{Time saved} + \text{Carb} + \text{Bio}) \tag{2}$$

where 'Morb' is the value of the decrease in morbidity experienced when switching cooking technology, 'Mort' is the value of the decrease in mortality, 'Time saved' is the value of time saved, 'Carb' is the value of the decrease in carbon emissions and 'Bio' is the value of the benefits related to the loss of other environmental services due to biomass harvesting[5]. As noted in ref. 5, the costs in the latter term are difficult to specify in a spatially explicit manner owing to a lack of reliable data, hence this Bio-parameter is omitted.

The costs in equation (1) are defined as in equation (3)[5]:

$$\text{Costs} = \text{Capital} + \text{O\&M} + \text{Fuel} + \text{Prog} + \text{Learn} \tag{3}$$

where 'Capital' is the capital cost of a stove, 'O&M' is the operation and maintenance cost, 'Fuel' is the fuel cost, 'Prog' is the cost of technology promotion (including marketing) and 'Learn' is the value of the time it takes to learn how to use the new technology[5]. In our study, we omit 'Prog' and 'Learn' since data regarding these costs are limited, and because it is not immediately clear how they would translate into differentially higher costs for the alternative technologies we analyse. Given these omissions, the net benefits of the various alternatives relative to the status quo should be considered an upper bound that would not be realized in locations where intensive promotion (and its associated costs) would be needed to induce adoption. Another way of interpreting the net social benefits calculated in a given location is that these represent an upper bound on the programme cost for the suite of interventions and complementary investments that could be made while still allowing society to break-even from a net-benefits perspective.

The net benefits are thus described in equation (4):

$$\begin{aligned}\text{Net benefit} &= (\text{Morb} + \text{Mort} + \text{Time saved} + \text{Carb})\\ &- (\text{Capital} + \text{O\&M} + \text{Fuel})\end{aligned} \tag{4}$$

Given this disaggregation of benefits and costs, scenarios can be explored using different combinations based on the preference of OnStove users (for example, decision-makers). In this study, for instance, we differentiate between social and private benefits. The sections below outline in more detail the components of equation (4).

Morbidity and mortality reductions

The morbidity and mortality calculations are similar in nature, therefore we describe them simultaneously. They are included as benefits since cleaner cookstoves usually decrease morbidity and mortality. For specific input values, refer to the morbidity and mortality section of the Supplementary Information.

We use the relative risk (RR) and population attributable fraction (PAF) equations proposed in ref. 36 to determine the relative risk of contracting (and dying of) HAP-related lung cancer (LC), acute lower respiratory infection (ALRI), ischaemic heart disease (IHD), chronic obstructive pulmonary disease (COPD) and stroke. The RR depends on the concentration of HAP; we therefore use the 24 h particulate matter 2.5 ($PM_{2.5}$) concentration of different stoves. This concentration is then multiplied by an exposure adjustment factor (ε, 0.51 for traditional biomass and 0.71 for all other stoves), included to account for potential behavioural change that results from switching to a cleaner stove. This is in line with what is done in the BAR-HAP model[32].

Equation (5) is then used to determine the RR associated with each disease[36]:

$$\begin{cases} \text{if } \varepsilon \times 24 - h \text{ PM2.5 concentration} < z_{rf},\ \text{RR} = 1 \\ \text{if } \varepsilon \times 24 - \text{h PM2.5 concentration} \geq z_{rf}, \\ RR = 1 + \alpha \times \left(1 - e^{(-\beta \times (\varepsilon \times 24 - \text{h PM2.5 concentration} - z_{rf})^{\delta})}\right) \end{cases} \tag{5}$$

where RR is the relative risk associated with each disease (LC, IHD, COPD, ALRI and stroke), and α, β, δ and z_{rf} are disease-specific constants determined experimentally. The equation ensures that the RR increases with increasing concentration of HAP at a decreasing rate (such that the marginal health damage of increased HAP exposure eventually tapers off)[36].

The disease-specific constants α, β, δ and z_{rf} are determined in ref. 36 by conducting 1,000 runs of their model per disease (results are reported at http://ghdx.healthdata.org/sites/default/files/record-attached-files/IHME_CRCurve_parameters.csv)[36]. In OnStove, we utilize the average value of the constants for each disease across the 1,000 runs (see the Supplementary Information).

The RR for each disease is used to determine the PAF, which is used to assess the public health impacts resulting from the population's exposure to HAP-related risks[37]. We determine the PAF for each stove *i* and disease *k* using equation (6)[6].

$$\text{PAF}_i = \frac{\text{sfu} \times (\text{RR}_k - 1)}{\text{sfu} \times (\text{RR}_k - 1) + 1} \tag{6}$$

where 'sfu' (solid-fuel users) is the share of the population not using clean cooking currently (see the Supplementary Information for country-specific values), and RR_k is the disease-specific RR determined using equation (5). Since the share of solid-fuel users differs between urban and rural areas, we diversify the PAF_i using geospatial datasets that identify which population cells are urban and which are rural.

Using the PAF_i together with disease-specific incidence and mortality rates allows us to determine the risk of morbidity and mortality (Morb_k and Mort_k, respectively) with equations (7) and (8). These equations are slightly modified versions of those applied in ref. 5. Equations (7) and (8) generate estimates of the reduced cases (Morb) and deaths (Mort) resulting from stove switching across the AOI .

$$\text{Morb}_k = \text{Population} \times (\text{PAF}_0 - \text{PAF}_i) \times \text{IR}_k \tag{7}$$

$$\text{Mort}_k = \text{Population} \times (\text{PAF}_0 - \text{PAF}_i) \times \text{MR}_k \tag{8}$$

where 'Population' is the total population (since OnStove is raster-based, the calculation is made on a cell-basis such that this term refers to the population in each cell), MR_k and IR_k are the mortality and incidence rates associated with each disease, PAF_0 is the PAF-value for the current situation and PAF_i pertains to the situation with the new stove. Since PAF_0 and PAF_i are differentiated by urban and rural areas, so are Morb_k and Mort_k. The MR_k and IR_k are country-specific (see the Supplementary Information).

We convert equations (7) and (8) to monetary values using the cost of illness (COI_k) and the VSL as described in ref. 5. Furthermore, ref. 5 suggests incorporating cessation lags (CL_{kt}) for each disease since the risk reductions do not occur immediately after a shift to cleaner technology. The final form of the morbidity and mortality equations are given in equations (9) and (10).

$$\text{Morb} = \sum_k \left(\sum_{t=1}^{5} \text{CL}_{kt} \times \text{COI}_k \times \frac{\text{Morb}_k}{(1+\delta)^{t-1}} \right) \tag{9}$$

$$\text{Mort} = \sum_k \left(\sum_{t=1}^{5} \text{CL}_{kt} \times \text{VSL} \times \frac{\text{Mort}_k}{(1+\delta)^{t-1}} \right) \tag{10}$$

where CL is the cessation lag (for disease *k* and time *t*), COI is the cost of illness (for disease *k*), VSL is the value of a statistical life, Morb_k is the reduction in cases (of disease *k*), Mort_k is the reduction of deaths (from disease *k*) and δ is the discount rate. See the Supplementary Information for the values of the constants used in these equations.

Time saved

The value of time saved captures the time costs of inefficient cooking due to both collection of fuels and cooking itself. Similar to the calculations of reduced morbidity and mortality, time saved is calculated relative to the situation with use of current technology. All stoves have specific cooking times (see the Supplementary Information). In addition, the use of wood or biogas entails a fuel collection time. This collection time is determined by calculating a least-cost path to the closest fuel supply in each cell (a spatial forest layer for wood and a livestock map for biogas). The cost used is a spatially explicit friction map describing the time needed to travel 1 m through each raster cell; hence, the least-cost path is equivalent to the fastest one. The time saved by switching stoves is then translated to a monetary (opportunity cost) value using the minimum wage of the country and a spatial wealth index layer. We use a spatially explicit relative wealth index available at 2.4 km resolution created by Facebook[38]. For three countries, Somalia, South Sudan and Sudan, this relative wealth index is not available, and sub-national poverty rates are used instead. Further details are available in the Supplementary Information.

The opportunity cost of firewood collection was previously computed on the basis of the time required to collect 1 kg of firewood, the probability of being employed and the wage rate[39]. A similar approach was also used in refs. 40 and [6], where factors between 0.3 and 0.9, and 0.1 and 0.5, respectively, were used on the basis of limited time valuation literature from specific locations and in industrializing countries. We use a factor ranging between 0.2 and 0.5 of the minimum wage, where the specific value applied in a location depends on the spatial wealth index. These assumptions notwithstanding, the general approach is consistent with other guidance in the cost-benefit literature that suggests use of 50% of the after-tax informal sector wage (which in many contexts is lower than the minimum wage)[41].

GHG emissions avoided

'Carb' accounts for the social benefits of reducing GHG emissions from use of cleaner technology and is based on equation (11).

$$\mathrm{Carb} = c^{\mathrm{CO_2}} \times \left(\mathrm{fueluse}_0 \times (\gamma_0 \times \mu_0)/\varepsilon_0 - \mathrm{fueluse}_i \times (\gamma_i \times \mu_i)/\varepsilon_i\right) \qquad (11)$$

where $c^{\mathrm{CO_2}}$ is the social cost of carbon (US\$ tonne^{-1}) from the 2021 update of the US Environmental Protection Agency[42]. This parameter is commonly used to estimate the long-term economic damage caused by GHG emissions[43]. 'Fueluse' is the amount of fuel used for cooking (kWh for electricity, kg for the rest), μ is the energy content of the fuel (MJ kWh^{-1} for electricity, MJ kg^{-1} for the rest) and ε is the fuel efficiency of the stove (%). Moreover, γ is a fuel-specific carbon intensity (kg GWh^{-1} for electricity, kg GJ^{-1} for the rest) that accounts for emissions of five relevant pollutants (carbon dioxide, methane, carbon monoxide, black carbon and organic carbon) and their 100 yr global warming potentials (GWP)[25] (see the Supplementary Information for stove emissions details). Subscript 0 denotes the baseline stove combination and i the new stove. International climate finance mechanisms have grown in importance as sources of funding for energy access and clean cooking projects[44]. This study assesses the GHG emissions connected to cooking energy technologies, and values reductions in these emissions at the social cost of carbon. Future work should consider how to best align carbon financing, including United Nations Framework Convention on Climate Change-backed climate finance instruments, with goals related to modern cooking energy access and reduced emissions.

Fuel use is taken as in ref. 40, which estimated that the final energy needed for cooking a 'standard meal' is 3.64 MJ[40]. Using this value, we estimate fuel needs using equation 12:

$$\mathrm{fueluse} = \frac{3.64}{\varepsilon} \times \mu \qquad (12)$$

The carbon intensity γ_i of fuel i is calculated using equation (13), where $\varepsilon_{i,j}$ is the emission factor of pollutant j from fuel i and GWP$_j$ is the 100 year global warming potential of pollutant j.

$$\gamma_i = \sum_j \varepsilon_{i,j} \times \mathrm{GWP}_j \qquad (13)$$

For biomass and charcoal, country-specific fractions of non-renewable biomass (fNRB), are used to exclude the carbon dioxide component from sustainably harvested woody biomass[17] (see the Supplementary Information for details).

Capital costs

The capital cost is a one-time cost paid upfront to obtain a new stove. In calculating this cost, we net out the salvage cost to adjust for the varying lifespan of different technologies as described in equations (14) and (15).

$$\mathrm{Capital} = \mathrm{inv} - \mathrm{salvage} \qquad (14)$$

$$\mathrm{Salvage} = \mathrm{inv} \times \left(1 - \frac{\text{used life}}{\text{technology life}}\right) \times \frac{1}{(1+\delta)^{\text{used life}}} \qquad (15)$$

where 'inv' represents the upfront cost of the new stove, 'salvage' assumes straight-line depreciation of the stove value over time (equation 15), 'used life' is the time frame of the analysis, 'technology life' is the stove's total lifetime and δ is the discount rate used to convert the salvage cost to a present value. The capital costs are generalized for all of SSA and the values used for each stove in equations (14) and (15) are reported in the Supplementary Information.

O&M costs

The O&M costs are paid on a yearly basis over the lifetime of each stove. For traditional stoves, we assume no O&M. For all other stoves, we assume an O&M of US\$3.7 yr^{-1} (ref. 32). Future O&M costs are discounted to present values using the relevant discount rate.

Fuel cost

Fuel costs are differentiated by fuel and location for specific stove types. Charcoal is assumed to be bought from vendors, LPG cost is spatially specified following ref. 45, fuel cost for electrical stoves is assumed to be equal to electricity generation cost, and the cost of biogas and wood are assumed to be zero since these fuels are usually produced and collected directly from the environment by end users (and are therefore valued using the opportunity cost of collection time). Yearly fuel costs are discounted to present values. Further details are provided in the Supplementary Information.

Limitations

OnStove has important limitations that future research should aim to address. First, country-specific stove shares for the current situation are only differentiated on the basis of urban and rural status. Future research should aim for a more spatially explicit specification of primary stove shares, perhaps based on modelling of the spatial determinants of such choices. This would enable a more detailed and nuanced modelling of the current situation, which in turn would allow for better understanding of the spatial distribution of benefits and costs of transitions to alternative technologies.

It is important to note that OnStove does not incorporate dynamics over time. Consequently, the transition to cleaner options over time is not captured. Future research should assess whether incorporating dynamics that indicate rising shares of users of improved and clean technology would change the results and importance of ICS technologies in the short and medium term.

Fuel stacking is common in many low- and middle-income countries. This phenomenon can result from a lack of reliable fuel supply, fuel-price fluctuations, perceived co-benefits of fuels, or cultural preferences. We have not considered fuel stacking in the analysis, largely because of data gaps. Energy Sector Management Assistance Program's Multi-Tier Framework surveys[46] offer the potential to begin to bridge this gap and could potentially be incorporated moving forward as more country datasets become available. Furthermore, OnStove takes account of the added capacity and investment needed to ensure that the increased demand for electricity due to electric cooking can be met. However, we do not model how electricity access (via grid extension or decentralized electrification) may develop. Future research should therefore link this tool with electrification models to overcome the 'mutual neglect' between SDG 7 targets[26–28]. Future research should also aim to better model affordability issues. The stoves with the highest net-benefits are not necessarily affordable, and our work only begins to investigate and discuss the affordability challenge and the role of liquidity constraints.

Moreover, it is important to note that the net-benefit equations have been applied to nine different stove types in our analysis. Hence, a number of potential cooking solutions have been omitted. A notable example is the growing set of cooking appliances powered by off-grid electricity solutions. Such 'eCooking' solutions have been shown viable in recent studies, and their advantages will further become apparent as the cost of renewable off-grid systems decrease, or where the electrical grid remains unreliable[28,47]. Future research should consider the role of these eCooking alternatives in the optimal stove mix.

Finally, although there is a clear divergence between the technologies that would be used under a socially optimal cooking technology mix and the actual situation in SSA, OnStove does not facilitate understanding of which policies could most cost-effectively close that gap. It may be the case that some interventions cannot be justified because their costs exceed the social net-benefits of the transitions they would induce. In addition, some interventions may be more cost-effective than others. Future work should consider the costs of a menu of different policies, for example building on existing non-spatial modelling approaches such as those presented in the BAR-HAP model[48].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The input data and outputs from the two main scenarios are available through a permanent database (https://data.mendeley.com/datasets/7y943f6wf8 [49]). The database includes all socio- and techno-economic files developed for this paper, as well as the sensitivity analysis summarized in the Supplementary Information. Apart from the non-GIS inputs, all processed geospatial layers are also included in the database together with their original sources and documentation of how they were altered for this study.

Code availability

The latest version of OnStove is available at https://github.com/Open-Source-Spatial-Clean-Cooking-Tool/OnStove. The repository includes instructions on how to install the necessary packages and run the analysis as well as a simple Jupyter Notebook interface example. The official documentation of OnStove is also available through Read the Docs (https://onstove-documentation.readthedocs.io/en/latest/?badge=latest). This documentation includes information on all tools developed for the analysis, ranging from the different geoprocessing tools used to the net-benefit equations and visualization tools. The version of OnStove used in this analysis is v0.1.2 (https://doi.org/10.5281/zenodo.7185176).

References

1. *WHO Indoor Air Quality Guidelines: Household Fuel Combustion* (WHO, 2014).
2. *Tracking SDG 7: The Energy Progress Report* (IEA, IRENA, UN Statistics Division, World Bank & WHO, 2022).
3. *The Sustainable Development Goals Report 2021* (United Nations, 2021).
4. Nerini, F. F. et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* **3**, 10–15 (2018).
5. Jeuland, M., Tan Soo, J.-S. & Shindell, D. The need for policies to reduce the costs of cleaner cooking in low income settings: implications from systematic analysis of costs and benefits. *Energy Policy* **121**, 275–285 (2018).
6. Jeuland, M. A. & Pattanayak, S. K. Benefits and costs of improved cookstoves: assessing the implications of variability in health, forest and climate impacts. *PLoS ONE* **7**, e30338 (2012).
7. Puzzolo, E., Pope, D., Stanistreet, D., Rehfuess, E. A. & Bruce, N. G. Clean fuels for resource-poor settings: a systematic review of barriers and enablers to adoption and sustained use. *Environ. Res.* **146**, 218–234 (2016).
8. Pattanayak, S. K. et al. Experimental evidence on promotion of electric and improved biomass cookstoves. *Proc. Natl Acad. Sci. USA* **116**, 13282–13287 (2019).
9. Bharadwaj, B., Malakar, Y., Herington, M. & Ashworth, P. Context matters: unpacking decision-making, external influences and spatial factors on clean cooking transitions in Nepal. *Energy Res. Soc. Sci.* **85**, 102408 (2022).
10. Beltramo, T., Blalock, G., Levine, D. I. & Simons, A. M. The effect of marketing messages and payment over time on willingness to pay for fuel-efficient cookstoves. *J. Econ. Behav. Organ.* **118**, 333–345 (2015).
11. Bensch, G., Grimm, M. & Peters, J. Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. *J. Econ. Behav. Organ.* **116**, 187–205 (2015).
12. Das, I. et al. *A virtuous cycle. Reviewing the Evidence on Women's Empowerment and Energy Access, Frameworks, Metrics and Methods* (Duke University, 2020).
13. Mentis, D. et al. Lighting the world: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa. *Environ. Res. Lett.* **12**, 085003 (2017).
14. Szabó, S., Bódis, K., Huld, T. & Moner-Girona, M. Sustainable energy planning: leapfrogging the energy poverty gap in Africa. *Renew. Sustain. Energy Rev.* **28**, 500–509 (2013).
15. Serrano-Medrano, M., Arias-Chalico, T., Ghilardi, A. & Masera, O. Spatial and temporal projection of fuelwood and charcoal consumption in Mexico. *Energy Sustain. Dev.* **19**, 39–46 (2014).
16. 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).
17. Bailis, R., Drigo, R., Ghilardi, A. & Masera, O. The carbon footprint of traditional woodfuels. *Nat. Clim. Change* **5**, 266–272 (2015).
18. Krishnapriya, P. P., Chandrasekaran, M., Jeuland, M. & Pattanayak, S. K. Do improved cookstoves save time and improve gender outcomes? Evidence from six developing countries. *Energy Econ.* **102**, 105456 (2021).
19. Mobarak, A. M. & Saldanha, N. A. Remove barriers to technology adoption for people in poverty. *Nat. Hum. Behav.* **6**, 480–482 (2022).
20. Kar, A. & Zerriffi, H. From cookstove acquisition to cooking transition: framing the behavioural aspects of cookstove interventions. *Energy Res. Soc. Sci.* **42**, 23–33 (2018).
21. Ruiz-Mercado, I. & Masera, O. Patterns of stove use in the context of fuel–device stacking: rationale and implications. *EcoHealth* **12**, 42–56 (2015).
22. Perros, T., Allison, A. L., Tomei, J. & Parikh, P. Behavioural factors that drive stacking with traditional cooking fuels using the COM-B model. *Nat. Energy* **7**, 886–898 (2022).
23. *Opening Opportunities, Closing Gaps: Advancing Gender-Equal Benefits in Clean Cooking Operations* (Energy Sector Management Assistance Program, 2022).
24. Fisher, S. et al. Air pollution and development in Africa: impacts on health, the economy, and human capital. *Lancet Planet. Health* **5**, e681–e688 (2021).
25. Dagnachew, A. G., Lucas, P. L., van Vuuren, D. P. & Hof, A. F. *Towards Universal Access to Clean Cooking Solutions in Sub-Saharan Africa* (PBL, 2018).
26. Yumkella, K., Batchelor, S., Haselip, J. A. (ed.), & Brown, E. *Scaling Up Investment in Climate Technologies: Pathways to Realising Technology Development and Transfer in Support of the Paris Agreement* 13–26 (UDP Perspectives Series, 2021).
27. Newell, P. & Daley, F. Cooking up an electric revolution: the political economy of e-cooking. *Energy Res. Soc. Sci.* **91**, 102730 (2022).
28. Batchelor, S. et al. Mutual support—modern energy planning inclusive of cooking—a review of research into action in Africa and Asia since 2018. *Energies* **15**, 5805 (2022).
29. Gill-Wiehl, A., Ray, I. & Kammen, D. Is clean cooking affordable? A review. *Renew. Sustain. Energy Rev.* **151**, 111537 (2021).
30. Ray, I. & Smith, K. R. Towards safe drinking water and clean cooking for all. *Lancet Glob. Health* **9**, e361–e365 (2021).
31. Pachauri, S., Poblete-Cazenave, M., Aktas, A. & Gidden, M. J. Access to clean cooking services in energy and emission scenarios after COVID-19. *Nat. Energy* **6**, 1067–1076 (2021).
32. Das, I. et al. The benefits of action to reduce household air pollution (BAR-HAP) model: a new decision support tool. *PLoS ONE* **16**, e0245729 (2021).

33. Robinson, L. A., Hammitt, J. K. & O'Keeffe, L. Valuing mortality risk reductions in global benefit-cost analysis. *J. Benefit Cost Anal.* **10**, 15–50 (2019).
34. Bruce, N. et al. The government-led initiative for LPG scale-up in Cameroon: programme development and initial evaluation. *Energy Sustain. Dev.* **46**, 103–110 (2018).
35. Stoner, O. et al. Household cooking fuel estimates at global and country level for 1990 to 2030. *Nat. Commun.* **12**, 5793 (2021).
36. Burnett, R. T. et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* **122**, 397–403 (2014).
37. Mansournia, M. A. & Altman, D. G. Population attributable fraction. *BMJ* **360**, k757 (2018).
38. Chi, G., Fang, H., Chatterjee, S. & Blumenstock, J. E. Microestimates of wealth for all low- and middle-income countries. *Proc. Natl Acad. Sci. USA* **119**, e2113658119 (2022).
39. Hosier, R. H. *Energy Use in Rural Kenya: Household Demand and Rural Transformation* (Scandinavian Institute of African Studies, Beijer Institute, 1985).
40. Nerini, F. F., Ray, C. & Boulkaid, Y. The cost of cooking a meal. The case of Nyeri County, Kenya. *Environ. Res. Lett.* **12**, 065007 (2017).
41. Whittington, D. & Cook, J. Valuing changes in time use in low- and middle-income countries. *J. Benefit Cost Anal.* **10**, 51–72 (2019).
42. *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide: Interim Estimates under Executive Order 13990* (Environmental Protection Agency, 2021).
43. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nat. Clim. Change* **8**, 895–900 (2018).
44. Michaelowa, A., Hoch, S., Weber, A.-K., Kassaye, R. & Hailu, T. Mobilising private climate finance for sustainable energy access and climate change mitigation in Sub-Saharan Africa. *Clim. Policy* **21**, 47–62 (2021).
45. Szabó, S., Bódis, K., Huld, T. & Moner-Girona, M. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. *Environ. Res. Lett.* **6**, 034002 (2011).
46. *Multi-Tier Framework for Cooking: A Comprehensive Assessment Method to Measure Access to Modern Energy Cooking Services* (World Bank, 2020).
47. *Cooking with Electricity: A Cost Perspective* (Energy Sector Management Assistance Program, 2020).
48. *Benefits of Action to Reduce Household Air Pollution Tool* (WHO, 2021).
49. Khavari, B., Ramirez, C., Jeuland, M. & Fuso Nerini, F. OnStove inputs and outputs. *Mendeley Data* https://doi.org/10.17632/7y943f6wf8.2 (2022).

Acknowledgements

The work done at KTH with regard to this research was partially supported by the Clean Cooking Alliance (CCA). We thank A. Oberholzer (CCA), A. Gurung (CCA), D. Mentis (WRI), S. Sinclair-Lecaros (WRI) and D. Khatiwada (KTH) for valuable inputs and discussions. Neither these individuals nor the CCA should be held responsible for any erroneous facts or interpretations presented in this paper. These are solely the responsibility of the authors.

Author contributions

B.K. and C.R. contributed equally to the conceptualization, methodology, software, validation, original draft and revisions. M.J. supported the conceptualization, validation, review and revisions. F.F.N. supervised the project, secured funding and supported the conceptualization, review and revisions.

Funding

Open access funding provided by Royal Institute of Technology

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41893-022-01039-8.

Correspondence and requests for materials should be addressed to Babak Khavari, Camilo Ramirez or Francesco Fuso Nerini.

Peer review information *Nature Sustainability* thanks Sally Goldin, Ed Brown, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

nature portfolio

Corresponding author(s): Babak Khavari, Camilo Ramirez, Francesco Fuso Nerini

Last updated by author(s): Nov 28, 2022

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☒	☐	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☒	☐	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All data used is of open source nature and shared in the paper, as specified in the data and code availability sections
Data analysis	All tools and models used in this paper are open source, as specified in the methods, data and code availability sections

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

Data availability

The input data and outputs from the two main scenarios are available through a permanent database (https://data.mendeley.com/datasets/7y943f6wf849). The database includes all socio- and techno-economic files developed for this paper, as well as the sensitivity analysis summarized in the Supplementary File. Apart from the non-GIS inputs, all processed geospatial layers are also included in the database together with their original sources and documentation of how they were altered for this study.

Code availability

The latest version of OnStove is available at https://github.com/Open-Source-Spatial-Clean-Cooking-Tool/OnStove. The repository includes instructions on how to install the necessary packages and run the analysis as well as a simple Jupyter Notebook interface example. The official documentation of OnStove is also available through Read the Docs (https://onstove-documentation.readthedocs.io/en/latest/?badge=latest). This documentation includes information on all tools developed for the analysis, ranging from the different geoprocessing tools used to the net-benefit equations and visualization tools. The version of OnStove used in this analysis is v0.1.2 (DOI: 10.5281/zenodo.7185176).

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	no human research participants were involved in the study
Population characteristics	no human research participants were involved in the study
Recruitment	no human research participants were involved in the study
Ethics oversight	no human research participants were involved in the study

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	For the study, We develop OnStove, an open-source spatial tool comparing the relative potential of different cookstoves based on their costs and benefits, and apply it to Sub saharan Africa. We use mixed qualitative and quantitative methods.
Research sample	Open-source geospatial data.
Sampling strategy	This is not applicable, as no primary data was collected.
Data collection	All data is open and collected via PC.
Timing	Data inputs are all referred to existing sources, with different time of publishing. No primary data was collected.
Data exclusions	This is not applicable, as no primary data was collected.
Non-participation	This is not applicable, as no primary data was collected.
Randomization	This is not applicable, as no primary data was collected.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging