Understanding the clean cooking policy challenge in sub-Saharan Africa using a geospatial approach

Babak Khavari
KTH Royal Institute of Technology
Camilo Ramirez
KTH Royal Institute of Technology
Marc Jeuland
Duke University https://orcid.org/0000-0001-8325-2622
Francesco Fuso Nerini (francesco.fusonerini@energy.kth.se)
KTH Royal Institute of Technology https://orcid.org/0000-0002-4770-4051

Article

Keywords: clean cooking, geospatial analysis, cost benefit analysis, sub-Saharan Africa, market failure

Posted Date: May 20th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1650097/v1

Version of Record: A version of this preprint was published at Nature Sustainability on January 12th, 2023. See the published version at https://doi.org/10.1038/s41893-022-01039-8.

Abstract

Universal clean cooking is one of the key targets under Sustainable Development Goal (SDG) 7, and has implications for several other SDGs, such as good health and well-being, gender equality and the climate goals. Yet, 2.6 billion people globally still lack access to clean cooking. The situation is especially dire in sub-Saharan Africa (SSA), where only 16% use clean stoves and fuels. We develop, and apply to SSA, the first open-source spatial tool comparing the relative potential of different cookstoves based on their costs and benefits. Our results suggest a severe market failure as the currently most used solution, traditional cookstoves, have the lowest social net-benefit nearly everywhere in SSA. Correcting this failure would deliver significant health, time and emission benefits. The presence of severe market failures and behavioral obstacles require targeted policies to both increase the understanding and internalize benefits and externalities from the adoption of clean cooking.

Introduction

In 2015 the UN general assembly agreed on an ambitious set of 17 Sustainable Development Goals (SDGs). Amongst them is target 7.1, universal access to energy, including electricity and clean cooking, by 2030[1]. This target is closely related to many other SDG-targets, either through synergies or trade-offs[2]. Progress towards the universal clean cooking target has proven particularly difficult. As of 2020, roughly 2.6 billion people still lacked access to clean cooking globally and relied on traditional fuels to reach their daily cooking needs[3]. Such practices are estimated to cause approximately 4 million pre-mature deaths annually and impede progress on gender equality and environmental quality goals[4,5]. The lack of clean cooking is especially pronounced in sub-Saharan Africa (SSA), where the number of people without access to clean cooking increased by almost 50% between 2000 and 2020[3].

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[1,6–8]. To support efforts towards achieving universal access to modern fuels for cooking, here we present the first open-source, scalable and reproducible spatial tool comparing cooking solutions (OnStove), as well as its first application for SSA. In terms of methodological novelty, while Geographic Information Systems (GIS) have been widely used to support electricity access strategies and least-cost electrification planning[9,10], GIS has not been used to date to systematically assess and compare the relative potentials of clean cooking solutions. OnStove can help increase understanding of how fuel availability, access to infrastructure, and relative fuel prices change across a study area, which in turn influences investment opportunities, and then inform the most appropriate promotion strategies. For policy-makers in SSA, the use of GIS can help to clarify where transitions to improved technology are currently lagging relative to their potentials, and thereby facilitate prioritization of greater policy and investment supports.

Here, we estimate and describe the costs and benefits of implementing universal clean cooking in SSA by comparing cooking solutions over every sq. km in the region. Furthermore, we identify factors that may inhibit or catalyze the adoption of clean cooking, such as lack of economic opportunity, issues in supply chains or low availability of specific technologies (e.g. no access to electricity). We also discuss the technical and political options that can speed up achievement of universal access to clean cooking.

Cooking in SSA – a market failure

Our results serve to highlight the important role that critical market failures and behavioral obstacles would appear to play in the current choice and distribution of cooking technologies across SSA. Most people in the region still rely on traditional stoves for cooking, as externalities connected to stove-switching (e.g. many of their health effects, the value of time saved, and environmental damages) do not appear to be properly quantified, understood, or internalized. We model two perspectives, one social and one private. The social perspective accounts for all private benefits – health costs avoided and the value of time saved, plus externalities such as greenhouse gas (GHG) emissions and health spillovers avoided. It applies a discount rate of 3% to account for the value of all expenditures and benefits over time. Results from the analysis indicate that the social optimum based on current infrastructure corresponds to a cooking energy situation with 771 million people primarily using LPG stoves, 350 million using electrical stoves, 13 million using biogas stoves and around 20,000 primarily using improved cookstoves (charcoal ICS or biomass ICS) (Fig. 1a). When evaluated from a social perspective, the OnStove cost-benefit analysis shows that traditional biomass and charcoal stoves would not deliver the highest net-benefit in anywhere in the region (Fig. 1). This is in stark contrast with the current situation in SSA, where 84% of the population relies primarily on such traditional technology[3]. This indicates the extreme disconnect between the cooking options that are ideal for social well-being, and those that people are actually using.

When taking into account private benefits only, i.e. reduced morbidity, mortality and time spent collecting fuels and cooking within stove-adopting households, and applying a discount rate of 15% that is more consistent with individual time preferences, results continue to show a large disconnect between current decisions and optimal outcomes. This supports further a claim of substantial market failure, in that markets are not delivering solutions that would benefit many people, as well as highlighting the severity of behavioral obstacles to cleaner cooking. Even in this model framing, most people in the region (~78%) should use clean cooking solutions (Fig 22), simply for the private benefits that these technologies deliver. The remaining 22% would use transitional stoves such as charcoal ICS or biomass ICS. LPG is again the most prevalent technology in the stove mix as the primary stove for around 830 million people, followed by charcoal ICS (232 million), electricity (45 million), improved biomass cookstoves (20 million), and biogas (8 million) (Fig 22a). The larger presence of transitional stoves in the private scenario highlights the reality that a large share of the population in SSA would not achieve positive net-benefits themselves from switching to clean solutions. Major contributors to reducing benefits include the relatively low value of time (i.e. low minimum wage and (or) unequal distribution of wealth) and low Value of Statistical Life (VSL) across many countries in SSA. Equally striking, however, is the fact that many households in SSA who would appear to benefit privately from using improved or clean technology are still primarily reliant on traditional cookstoves. The fact that they do not adopt such technologies is clear evidence that other barriers – discussed further below – remain determinant.

ICS as transition

We included two ICS options in our analysis (biomass and charcoal) which have been classified as "improved" or transitional[11]. 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 more similar to that of traditional stoves, which limits the learning effort needed for their operation[6]. These factors contribute to ICS potentially playing an important role as transitional stoves on the path to more widespread use of clean options.

In the optimal social benefits scenario, ICS would only be used in the Democratic republic of Congo, Mali, Niger and Rwanda, by a very limited number of people (~20,000). Their low share is partly due to GHG-emissions and the fraction of non-renewable biomass. The production of charcoal is an emission-intensive process[12] and larger shares of non-renewable biomass have an impact on the costs of biomass. The role of these factors is further highlighted by the fact that charcoal ICS become much more prevalent in the private benefits scenario, in which emissions reductions are the largest category of benefits (or for charcoal, costs) omitted from the net-benefit equation. Indeed, charcoal ICS become the second most used stove option across SSA under this private perspective. In general, charcoal ICS is also primarily used in countries with lower VSLs (i.e., where health benefits are valued less). Similarly, the prevalence of biomass ICS in the optimal stove mix increases in the private scenario as well. Two countries, Burundi and Malawi, have a majority of their population benefiting the most from biomass ICS (81 and 54% respectively). For Burundi, this is a result of the country having the lowest VSL and minimum wage amongst the full set of countries studied. As a result, the value of reduced mortality and the opportunity cost gained from using more efficient technologies are comparatively low. For Malawi, the primary reason for high shares of biomass ICS is the low fuel collection time (on average the travel time to woody biomass is less than 6 minutes).

Overall, these results illustrate that including a more restricted set of benefits, or applying lower valuations to them, tend to result in the cheaper ICS technologies becoming more attractive. Furthermore, time savings and health benefits may not always be salient to households, and particularly among household decision-makers. Those individuals – typically male head 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 – who tend to be women[13]. Thus, clarifying how such household "internalities" can be reduced with use of more efficient stoves may increase the incentive for adopting ICS. Prior work suggests that this can be challenging, however, and that financial aspects – and liquidity constraints in particular – often dominate the household decision calculus[14,15].

Achieving the potential of clean stoves requires multi-pronged interventions

Markets alone are falling dramatically to deliver on the promise and myriad benefits of clean cooking. Achieving enhanced alignment between household cooking technology use and the socially, or even privately, optimal technology use will require concerted, coordinated policy action. In the optimal social benefits scenario, virtually everyone in SSA would use clean cooking solutions, with LPG as the most important stove option (for 68% of the population), followed by electrical stoves (31%). The latter, share of electrical cooking, is significant as the current electricity access rate in SSA is estimated to be 47.9%,[16] and OnStove does not account for future improvements in electricity access. Thus, electricity is more often the preferred solution over LPG, from a social net-benefits perspective, where it is available. Indeed, integrated planning efforts that consider expanded access to universal electricity and clean cooking would likely substantially increase the optimal share of electric cooking.

In the scenario maximizing private benefits, meanwhile, LPG stoves become more competitive than electric ones, largely because of the lack of accounting for GHG emissions, where electricity has a relative advantage given the considerable reliance on renewable power generation in SSA. At the same time, the total share of clean stoves decrease, as charcoal cooking is privately attractive in a number of locations. Thus, omission of social benefits (i.e. spillover effects from kitchen emissions, avoided GHG-emissions and the social costs of illness borne by the public health system) renders the benefit of adopting clean stoves too small to offset their higher costs for a sizeable share of the population. Externalities are a classic example of market failure; achieving the social optimum in their presence requires either a) subsidies that would reduce the private user costs of clean technology, or alternatively, b) taxes that would raise the private user costs of polluting solutions. Given that the latter policy would be hard to implement for traditional stoves and fuels that are rarely purchased, the former approach is recommended.

As noted above, household cooking technology choices in SSA at this time are highly divergent even from the privately optimal technology mix. This is likely due to underdeveloped supply chains for improved and appropriate technology[17], household internalities that create a discrepancy between the benefits that decision-makers perceive and the real benefits to household members[18], liquidity constraints that inhibit adoption of new solutions[14,15], and even social influences whereby many people simply mimic the behaviors of others around them, even when those behaviors are costly[19]. Fuel-stacking also play a role in the challenge[20,21]. Addressing this complex web of factors and barriers will require coordinated policies, interventions, and cooperation between governments and the private sector suppliers of clean solutions[17]. Besides subsidies, the actions needed include information provision, social marketing that especially targets influential sub-groups, empowerment of marginalized populations (particularly women), and supply chain and market strengthening.

The urgency of correcting the market failure

The use of traditional stoves carries with it numerous disadvantages. People forced to rely on traditional fuels often spend considerable time collecting fuel from the environment, and preparing their food. For example, it is estimated that rural households using traditional stoves spend approximately 1.3 hours daily on collecting biomass fuels[22]. This burden often falls on women and children. Much of the biomass collected is collected in a non-sustainable manner, contributing to forest degradation, which increases net

GHG-emissions[23]. Furthermore, around 700,000 deaths in Africa in 2019 where attributed to HAP[24]. OnStove captures these aspects of traditional cooking by monetizing the benefits of time saved, avoided emissions, and reduced morbidity and mortality from transitions to cleaner options.

When the optimal technology is used (based on a social benefits accounting), the impacts of adopting the technologies with the highest net-benefits in SSA amount to 463,000 averted deaths per year. Furthermore, health costs of 66 billion USD are avoided annually. This decrease in deaths and health costs can be attributed to the very high shares of LPG and electrical stoves, which dramatically reduce exposures to harmful particulate emissions, and therefore result in fewer cases of disease and deaths. With optimal technology selected solely based on a private accounting of costs and benefits, the number of deaths and health costs avoided would sum up to 330,000 and 44 billion USD respectively. While this is a significant improvement from the current situation, it is considerably lower than that which is optimal under the full social perspective. This can be attributed to the significantly higher share of transitional options that would be selected when spillover benefits are ignored.

The total time saved in both scenarios averages around an hour per household and day. This similarity is expected as cooking times are comparable among the clean stoves modeled. Furthermore, fuel-types requiring substantial collection time (biomass and biogas) are not widely used in either scenario. This is important as the time spent collecting fuel contributes the most to the total time used. The emissions avoided in the social scenario amount to 315 billion MT of CO_2-eq. The private scenario, while not explicitly considering stove emissions, still leads to a decrease of emissions (210 billion MT of CO_2-eq), simply because households would still shift to much more efficient technology under those assumptions.

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 technology, and these benefits well outweigh the resulting stove and fuel costs (Fig 3). In the social benefits scenario, the benefits are higher across all categories, because the technologies favored under that perspective are the cleanest and most efficient.

The costs of correcting market failures

The costs of the two scenarios differ considerably. While the net-investments of adopting the stove mix delivering the highest private net-benefits would reach 3 billion USD per year, the net-investments of the social perspective would amount to 7.5 billion USD per year. These costs include the costs of investing in new stoves as well as capacity upgrades needed to allow the existing grid to sustain electrical cooking. This can be contrasted to the annual investments needed to reach universal residential electrification, estimated at 41 billion USD[3].

The largest share of costs is associated with buying fuel needed for cooking (either electricity, LPG or charcoal). The fuel costs for the technology mix selected under the optimal private benefits framing amount to 11.8 billion USD per year, which rises to approximately 14.5 billion USD for the optimal social benefits technology mix. Here it is important to consider that all costs (and benefits) are relative to the baseline stove situation. Therefore, if the stove with the highest net benefits in a given settlement has a lower fuel-cost than the baseline, the fuel cost in that specific settlement will be negative. This occurs with adoption of biomass ICS, biogas and, in some countries, charcoal ICS and electricity. In the case of biomass ICS and biogas this is because these stoves do not require fuel purchases, and fuel collection costs decline relative to the traditional stoves which are less efficient. In the case of charcoal ICS it occurs in regions were traditional charcoal is currently frequently used, thus fuel costs are saved by switching to more efficient ICS stoves. In the case of electricity, it is due to low electricity costs in specific countries that lead to savings relative to other purchased baseline fuels with higher costs (LPG).

Sensitivity analysis

Uncertainty regarding the specific value of the many model parameters across the SSA region is substantial, and may influence the results. To assess the sensitivity of results to major assumptions, a screening of different variables was conducted. We ran 580 scenarios to assess the effects of 28 different parameters using the method of Morris[25,26]. This approach assesses the relative impact of different parameters included in the full social accounting of the net-benefit equation with regards to optimal stove shares, and resulting benefits and costs. Across the different parameters assessed, several factors are indicated as especially important (see Fig 4). This is in line with the point raised previously; it is important to understand the benefits of switching to cleaner alternatives in order to correct current market failures. For example, if households underestimate the health costs, and especially the mortality losses, of polluting fuels use this will have a major impact on their stove choices. The parameters selected, as well as their ranges, the method of Morris and the detailed results of the screening exercise are described in Supplementary File C.

Ways forward to universal access to clean cooking in SSA

The divergence between private and social benefits of clean cooking, globally and in SSA, has been identified as a major policy challenge in previous studies, that requires concerted policy actions to address[5–7,18]. That 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 various cooking energy technologies[27]. However, neither spatial patterns of this divergence, nor the implications for targeted policies and interventions, have previously been characterized. Here, we presented the first 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 all of SSA.

Indeed, a majority of people in the region currently use traditional biomass for cooking, but the socially optimal technologies across most locations are in fact 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 still no use of traditional stoves. The fact that existing technology use in SSA is so different from this private optimum serves to highlight the fact that markets alone are failing to provide technologies that would benefit many millions of people in the region.

Of course, so called transitional technologies, which are somewhat important in the privately optimal stove mix, still impose substantial health and environmental consequences relative to the cleanest technologies, i.e., biogas, LPG, and electric cooking. A different perspective that includes the full societal benefits yields an even higher share of clean technologies (mainly LPG and electricity), and almost completely removes transitional stoves from the set of optimal technologies. This further confirms the observation that the cooking market is not delivering on the promised benefits of a modern cooking transition. Instead, interventions – that address the myriad obstacles to dissemination of such technology, and especially address the affordability challenges – are needed across all countries of SSA in order to correct current behavioral challenges and market inefficiencies. This challenge is especially great in countries with low wages, severe wealth inequalities (and hence low health valuations), and lack of infrastructure such as effective LPG distribution networks, and access to electricity.

Education and decent employment options that raise the opportunity cost of time can also help overcome market inefficiencies related to time spent cooking with ineffective stoves and fuel collection. By strengthening the economy and providing access to quality education, time would be valued more by private individuals, who would see economic gains in finding work relative to the money saved from collecting fuels from the environment or using cheap, but highly inefficient, cooking technologies. Here, household internalities resulting from gender norms and lack of women's empowerment and work opportunities must also be addressed. Private and public health costs can be partly internalized with information and behavior change interventions that raise awareness about the health effects of traditional fuels, but economic development is also highly correlated with health valuations[28]. With targeted investments and subsidies to support initial adoption, general knowledge about clean cooking technologies and their versatility can be increased, which would in turn reduce public expenditures needed for treating HAP-related diseases. Fully in the sphere of spillovers, there is a need to internalize the costs of GHG-emissions by implementing carbon markets and leveraging carbon financing at large scale to reduce use of polluting fuels and incentivize sustainable harvesting of biomass.

Even so, internalizing health, time and environmental benefits will likely not suffice to achieve a successful cooking energy transition. There is a strong need for investment in complementary infrastructure and supply chains for clean cooking solutions. In electrified locations, for example, we find that electric cooking is more often than not the 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[29]. The high cost of biogas digesters calls for targeted subsidies to increase the competitiveness of small-scale biogas use for cooking, at least among the rural households who can utilize that technology. 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 develop the first geospatial cost-benefit based clean cooking tool, OnStove. OnStove is an open-source geospatial tool determining the net-benefit of different cooking solutions in every settlement of a given study area. The tool conducts a cost-benefit-analysis, taking into account benefits with regards to reduced morbidity, mortality and carbon emissions as well as time saved. The stove with the highest net-benefit (combined benefits minus combined costs) in each settlement is selected (see Fig. 5 for an overview of the methodology). The tool currently compares seven stove-types; traditional biomass and charcoal, biomass and charcoal ICS, LPG, biogas and electricity. The model is highly modular and enables easy exclusion of existing technologies and inclusion of new ones.

The sections below describe the input data needed for the tool, the modeling approach used for the current fuel shares in different settlements and the methods used in the cost-benefit analysis. Note that certain calculation outlined below may look different for specific stoves; for stove-specific calculations and input values, including information on their level of spatial aggregation, please refer to the Supplementary File B.

Inputs

OnStove's inputs are divided into three categories: GIS-datasets, a socio-economic specification file and a techno-economic specification file. GIS-datasets are needed in order to capture different spatial aspects of the Area of Interest (AOI). This is important as factors such as costs and time spent collecting fuels are spatially variable. Furthermore, certain stove options may not be suitable in specific areas if supply of associated fuels is not readily accessible (e.g. electrical stoves in regions without electricity access). The socio-economic file contains information related to the socio-economic situation in the AOI (e.g. the total population and share of electrified population). The techno-economic file contains data on the stoves (e.g. name of the stove, current share of market and investment costs). The techno-economic file also defines the stoves included in the analysis. If one wish to remove or add a stove to the analysis changes have to be done here. See Supplementary File A for a list of the different GIS-datasets used in the analysis, as well as the data entered in the socio-economic and techno-economic files.

Base-line

For calculation of the net-benefit equation it is important to know the current stove types in use across the AOI. In this study the usage of different stoves have been disaggregated between urban and rural settlements on a national basis. To do this, data from Stoner et al.[30] were used. Stoner et al. estimate the rates of cooking with different fuels globally, disaggregated to national level as well as urban and rural settlements, between the years of 1990 and 2030. Here, we used their urban and rural values for the year of 2020. Unless stated otherwise, the shares of cooking fuels in each cell of the AOI is assumed the same as the urban or rural values reported by Stoner et al. See Supplementary File B for the base-line values used in different countries.

Governing equation

The governing equation determining which stove is used in each settlement at the end of the analysis is a modified version a prior net-benefit specification[6]. In that approach, the net benefit of a cooking technology transition is calculated as the difference between the total benefits and total costs resulting from switching stoves (Eq. 1):

Net-benefit $= Benefits - Costs$ (1)

The calculation further specifies the benefits of Eq. 1 as described in Eq. 2 (Note that all parameters are described in monetary values):

$$Benefits = (Morbidity + Mortality + Timesaved + Carb + Bio)$$

2

Where; Morbidity is the decrease in morbidity experienced when switching stove, Mortality is the decrease in mortality experienced when switching stove, Time saved is the time saved by switching stove, Carb is the decrease in carbon emissions by switching and Bio are other environmental benefits related to the loss of environmental services due to non-sustainably harvested biomass[6]. As noted by Jeuland et. al.[6], costs associated with non-sustainable harvesting are very difficult to generalize and determine in a spatially explicit manner. Thus, due to lack of reliable data, the Bio-parameter is omitted.

The costs in Eq. 1 are defined as in Eq. 3[6]:

$$Costs = Capital + O\&M + Fuel + Prog + Learn$$

3

Where; *Capital* is the capital costs of the stove, *O&M* is the operation and maintenance cost of the stove, *Fuel* is the fuel cost, *Prog* is the cost of implementing the technology (including marketing and promotion) and *Learn* is the monetized value of the time it takes to learn how to use the new technology[6]. In our study, we omit the *Prog* cost since data are limited regarding the costs of marketing and promotion, and it is not immediately clear how they would translate into differentially higher costs for the alternative technologies we analyze. Moreover, *Learn* is also omitted for similar reasons. Given these omissions, the net-benefits of the various alternatives – relative to the status quo – should be considered an upper bound that might not be fully realized in locations where intensive promotion 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 program cost for the whole suite of interventions and complementary investments that could be made while still allowing society to break-even from a net-benefits perspective.

The net-benefit used in OnStove is thus described in Eq. 4:

$$\textit{Net-benefit} = (Morb + Mort + Timesaved + Carb) - (Capital + O\&M + Fuel) \quad (4)$$

Different scenarios can be discussed with stakeholders to decide which benefits and costs to include. For instance, one may differentiate between social and private benefits. The sections below outline in more detail all of the parameters included in Eq. 4.

Benefits

Morbidity and Mortality

The morbidity and mortality calculations are similar in nature and we therefore describe them simultaneously. They are included as benefits as cleaner cookstoves are assumed to decrease morbidity and mortality. The sections below describe the theory used in the methodology. For specific input values, please refer to the morbidity and mortality section of Supplementary File B.

We use the Relative Risk (RR) and Population Attributable Fraction (PAF) equations proposed by Burnett et al.[31] to determine the relative risk of contracting (and dying of) lung cancer (LC), acute lower respiratory infection (ARLI), ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD) and stroke caused by HAP. The RR is dependent on the concentration of HAP, we therefore use the 24-h $PM_{2.5}$ concentration of different stoves. The 24-h $PM_{2.5}$ concentration of each stove is multiplied by an exposure adjustment factor ( ). This factor (0.51, traditional biomass and 0.71, all other stoves) is included to account for potential behavioral change that results from switching to a cleaner stove. This is in line with what is used in the BAR-HAP model[27].

Using the 24-h $PM_{2.5}$ concentration Burnett et al. propose Eq. 5 to determine the RR associated with each disease[31]

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

Where; RR is the relative risk associated with each disease studied (LC, IHD, COPD, ALRI and stroke), and α, β, δ and z_{rf} are disease-specific constants determined experimentally. The form of the equation ensures that the RR increases with increasing concentration of HAP and eventually flattens out when RR reaches a specific concentration (at a specific point it is assumed that increased concentration of HAP no longer leads to a higher risk)[31].

Burnett et al. determine the disease-specific constants α, β, δ and z_{rf} by conducting 1,000 runs of their model per disease (results for each run is reported here)[31]. For the purpose of the OnStove application, we utilize the average value of the constants for each disease across the 1,000 runs (refer to Supplementary File B).

The RR for each disease is used in order to determine the PAF. PAF is often used to assess the public health impacts resulting from a population's exposure to a risk[32]. We determine the PAF for each stove *i* and disease *k*, using Eq. 6[7].

$$PAF_i = \frac{sfu * (RR_k - 1)}{sfu * (RR_k - 1) + 1}$$

6

Where; sfu (solid-fuel users) is the share of population not using clean cooking currently (for country specific values used for sfu see Supplementary File B) and RR_k is the disease-specific RR determined using Eq. 6. Since the share of solid-fuel users differ between urban and rural settlements, we similarly diversify PAF_i.

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 the equations used by Jeuland et al.[6] Equations 7 and 8 give the reduced cases (Morb) and reduced number of deaths (Mort) across the AOI resulting from fuel-switching.

$$Morb_k = Population * (PAF_0 - PAF_i) * IR_k$$

7

$$Mort_k = Population * (PAF_0 - PAF_i) * MR_k$$

8

Where; Population is the total population, MR_k is the mortality rate associated with the disease and IR_k is the incidence rate associated with the disease, PAF_0 is the PAF-value for the base-line and PAF_i is the PAF-value of the new stove. Since PAF_0 and PAF_i are diversified between urban and rural settlements, so is $Morb_k$ and $Mort_k$. Eqs. 7 and 8 are calculated for each cell in the AOI, hence the population parameter represents the population in each cell. The MR_k and IR_k, are diversified for each country, these values are reported in Supplementary File B.

We convert Eqs. 7 and 8 to monetary values using the Cost of Illness$(COI_k)$and the Value of Statistical Life(VSL)as described by Jeuland et al.[6] Furthermore, Jeuland et al. suggest incorporating cessation lags (CL_{kt}) for each equation due to reduction of risk of disease not coming instantaneously after changing to clean cooking. The final form of the morbidity and mortality equations are given in Eqs. 9 and 10.

$$Morb = \sum_k \left(\sum_{t=1}^{5} CL_{kt} * COI_k * \frac{Morb_k}{(1+\delta)^{t-1}} \right)$$

9

$$Mort = \sum_k \left(\sum_{t=1}^{5} CL_{kt} * VSL * \frac{Mort_k}{(1+\delta)^{t-1}} \right)$$

10

Where; CL is the cessation lag (as function of disease k and time t), COI is the cost of illness (as function of disease k), VSL is the value of statistical life, $Morb_k$ is reduced cases (of disease k), $Mort_k$ is reduced number of deaths (as result of disease k) and δ is the discount rate. As the calculations of $Morb_k$ and $Mort_k$ (Eqs. 7 and 8) are diversified by cell, so is the values of Morb and Mort. See Supplementary File B, for the values of the constants used in these equations.

Time saved

The time saved factor captures the costs of inefficient cooking in terms of time expenditures, both potential time needed for collection of fuels and time of cooking. Different fuels and stoves are assumed to have different collection and cooking times. Similar to the calculations of reduced morbidity and mortality, the time saved is calculated relative to the base-line.

The opportunity cost of time saved by switching stove is translated to monetary value using the minimum wage of the country (entered by the user in the socio-economic specification file) and a spatial wealth index layer. For the purpose of this analysis a relative wealth index available at 2.4 sq. km resolution created by Facebook has been used[33]. For three countries, Somalia, South Sudan and Sudan, Facebook has not produced a relative wealth index, thus for these countries sub-national poverty rates are used instead.

Hosier[34] computed the opportunity cost of collecting firewood by accounting for the time required to collect one kg of firewood, the probability of being employed, and the wage rate. This approach was also used by Nerini et al.[35] using a factor between 0.3–0.9 to account for the cost of opportunity of collecting firewood in the Nyeri County, Kenya. Moreover, Jeuland et al.[7] used a similar factor, the shadow value of time, where they defined a low to high range of the shadow value of time between 0.1 and 0.5 of the minimum wage. We use a factor ranging between 0.2 to 0.5 of the minimum wage (or poverty rate) to account for the probability of a person being employed depending on parameters such as their location and wealth. The reasoning behind altering the limits given by Jeuland et al. is to reduce the likelihood of valuing time at levels that are too low. Hence, by using the spatial wealth index as proxy to distribute the probability, we can diversify the opportunity cost from location to location. For stove specific calculations and values for time of cooking and collection please refer to Supplementary File B.

Carb

Carb accounts for the social environmental benefits connected to reduction of GHG-emissions following stove-switch. To determine Carb, Eq. 11 is used.

$$Carb = c^{CO_2} * (fueluse_o * (\gamma_0 * \mu_0)/\epsilon_0 - fueluse_i * (\gamma_i * \mu_i)/\epsilon_i)$$

11

Where; c^{CO_2} is the social cost of carbon (USD/MT) taken from the 2021 update by the United States Environmental Protection Agency[36]. This parameter, is commonly used to estimate the long term social economic damage caused from GHG-emissions[37]. $fueluse$ is the amount of fuel used for cooking (kWh for electricity, kg for other fuels), μ is the energy content of the fuel (MJ/kWh for electricity, MJ/kg for the rest) and ϵ is the fuel efficiency of the stove (%). Moreover, γ is the carbon intensity of the fuel (kg/GWh for electricity, kg/GJ for the rest) for which five different pollutants (carbon dioxide, methane, carbon monoxide, black carbon and organic carbon) in combination with their 100 year Global Warming Potential (GWP) are used[38] (see Supplementary File B for emissions of each stove). *0* denotes the baseline stove combination and, i the new stove.

Fuel use is estimated using Nerini et al.[35], they estimated that the final energy needed for cooking a standard meal is 3.64 MJ[35]. Using this value we estimate the fuel needed as described in Eq. 12:

$$fueluse = \frac{3.64}{\epsilon} * \mu$$

12

The carbon intensity γ_i of fuel i, is calculated according to Eq. 13. Where $\epsilon_{i,j}$ is the emission factor of pollutant j of fuel i and GWP_j the 100 year global warming potential of pollutant j.

$$\gamma_i = \sum_j \epsilon_{i,j} * GWP_j$$

13

For woody biomass fuels (i.e. biomass and charcoal), national factors of the fraction of non-renewable biomass are used to only account for the emissions from non-sustainably harvested woody biomass[23] (see Supplementary File B for details and national values).

Costs

Capital costs

The capital cost is a one-time cost paid up-front to attain the new stove. It deviates from the amortized costs used by Jeuland et al.[6] as we net-out the salvage cost from the capital cost adjusting for varying lifespans of different technologies as described in equations 14 and 15.

$Capital = inv$ - *salvage* (14)

Where; inv represents the upfront cost of the new stove and *salvage* is incorporated to take into account the varying lifetimes of different stoves, assuming a straight-line deprecation of the stove value. The *salvage* cost is calculated as described by Eq. 15.

$$Salvage = inv * \left(1 - \frac{usedlife}{technologylife}\right) * \frac{1}{(1 + dr)^{usedlife}}$$

15

Where; *used life* is the time frame of the analysis, *technology life* is the stove's total lifetime and dr is the discount rate used to discount the salvage cost of the stove to present value (see Supplementary File B for values regarding stove life).

The investment costs are generalized for all of SSA and values for each stove are reported in Supplementary File B.

O&M costs

The O&M costs are paid on a yearly basis during the entire lifetime of each stove. For traditional stoves, we assume no O&M. For all other stoves we assume an O&M of 3.7 USD/year[27]. Moreover, O&M costs are discounted to present value using the relevant discount rate.

Fuel cost

Fuel costs are diversified by fuel and location for specific stove types. Charcoal is assumed to be bought from vendors, LPG cost is diversified spatially following a similar methodology as in Szabó et al.[39], fuel cost for electrical stoves is assumed to be the electricity generation cost and the cost of biogas is zero as all biogas is assumed to be produced in-situ. The monetary cost of wood is also assumed to be zero as all wood is assumed to be collected by the users themselves (and therefore valued through the opportunity cost of time spent on collection, as described previously). Yearly fuel costs are discounted to present value using the relevant discount rate. For detailed information on the fuel costs, as well as associated calculations and values, please refer to Supplementary File B.

Limitations and future work

OnStove has several limitations that future research should aim at overcoming. Firstly, the base-line is currently a calibration based on the work of Stoner et al[30]. The results of Stoner et al. are disaggregated based on urban and rural divide, hence all urban cells have the same base-line shares of fuels, as do all rural. Future research should aim to understand in a more spatially-explicit manner how the choice of primary stove varies, perhaps based on modeling of the spatial determinants of such choices, and how these determinants can themselves be represented spatially. Doing so would enable a more detailed and nuanced modelling of the base-line, which in turn would allow for better understanding of the spatial distribution of benefits and costs of transitions to alternative technologies relative to that base-line. It would similarly be useful to improve spatial understanding of other model parameters such as mortality and incidence rates as well as electricity costs based on transmission and distribution costs.

It is important to note that OnStove does not incorporate dynamics over time. Consequently, there is a risk of underestimating the actual importance of ICS in the scenarios, as without proper temporal representation, the transition to cleaner options may not be captured adequately. 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 (mainly) the ICS technologies in the short- and medium-term.

Moreover, OnStove relies on data from Bailis et al.[23] to define the fNRB across each country. This data is crucial to estimate the GHG-emissions of the baseline and, therefore, the reduced emission from switching stoves. Currently, OnStove uses a fixed fNRB value for each country that does not get affected by changes in the demand for biomass. Such representation can be improved by increasing the spatial resolution of the fNRB accounting for regional balances of firewood demand and availability, leveraging spatially explicit data from each region. This should also include a coupling of the relationship between demand for firewood, on the one hand, and the availability and fNRB in each cell, on the other.

Fuel-stacking is a common practice in many low- and middle-income countries. This can be due to several reasons such as a lack of reliability of certain fuels, fluctuations in fuel prices or perceived co-benefits of fuels (e.g. space heating from using traditional biomass), and cultural preferences. OnStove does not enable modelling of fuel-stacking. This should be incorporated moving forward. Furthermore, there are aspects of OnStove that can be further developed, e.g. emissions of certain fuels or the expansion of the electricity network. Currently, we take into account the added capacity needed to ensure that the increased demand of electricity from electrical cooking is met, in terms of added investments and added emissions. However, we do not model how electricity access (via grid extension or decentralized electrification) may develop. Future research should aim at soft-linking the clean cooking tool with electrification tools in order to cover both of these major targets of Sustainable Development Goal 7. Future research should also aim at better modelling affordability issues with regards to stove switching. The stove with the highest net-benefit is not necessarily affordable, and while relative wealth and minimum wage have been used to determine the value of time, they are not used to account for affordability challenges and liquidity constraints. Spatial affordability distributions can help us gain insight on gaps that need to be addressed in order to reach the target of universal access to clean cooking.

Finally, though there is a clear divergence between the technologies that would be used under a socially optimal cooking technology mix and the actual technology mix 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 (on their own or in combinations) cannot be justified because their costs exceed the social net-benefits of such a switch. In addition, some policy interventions may be more cost-effective than others. Future work should consider the costs of a menu of different policies, perhaps building on the non-spatial modeling approach presented in the BAR-HAP model[40].

Declarations

Acknowledgements

The work done at KTH with regards to this research was partially supported by the Clean Cooking Alliance (CCA). Furthermore, the authors would like to acknowledge Alicia Oberholzer (CCA), Anobha Gurung (CCA), Dimitrios Mentis (WRI) and Santiago Sinclair-Lecaros (WRI) for their valuable inputs and discussions. Note that none of 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

Conceptualization, B.K., C.R., M.J. and F.F.N.; Methodology, B.K. and C.R.; Software, B.K. and C.R.; Validation, B.K., C.R. and M.J.; Original draft, B.K. and C.R.; Review, M.J. and F.F.N., Revisions, B.K., C.R., M.J. and F.F.N.; Supervision, F.F.N.

Competing interests

The authors declare no competing interests.

Data availability

The authors declare that all the data supporting the findings of this study are available within the paper and the Github repository mentioned in the methods.

References

1. United Nations. *The Sustainable Development Goals Report 2021*. (2021).
2. Nerini, F. F. *et al.* Mapping synergies and trade-offs between energy and the Sustainable Development Goals. Nat Energy **3**, 10–15 (2018).
3. IEA, IRENA, UNSD, World Bank & WHO. *Tracking SDG 7: The Energy Progress Report*. (2021).
4. Cameron, C. *et al.* Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. Nat Energy **1**, 1–5 (2016).

5. 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).
6. 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).
7. 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).
8. 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. Environmental Research **146**, 218–234 (2016).
9. 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).
10. Szabó, S., Bódis, K., Huld, T. & Moner-Girona, M. Sustainable energy planning: Leapfrogging the energy poverty gap in Africa. Renewable and Sustainable Energy Reviews **28**, 500–509 (2013).
11. World Health Organization. *WHO indoor air quality guidelines: household fuel combustion*. (2014).
12. Akagi, S. K. *et al. Emission factors for open and domestic biomass burning for use in atmospheric models*. https://acp.copernicus.org/preprints/10/27523/2010/acpd-10-27523-2010.pdf (2010) doi:10.5194/acpd-10-27523-2010.
13. 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 Economics **102**, 105456 (2021).
14. 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. Journal of Economic Behavior & Organization **118**, 333–345 (2015).
15. Bensch, G., Grimm, M. & Peters, J. Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. Journal of Economic Behavior & Organization **116**, 187–205 (2015).
16. Access to electricity – SDG7: Data and Projections – Analysis. *IEA* https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity.
17. Pattanayak, S. K. *et al.* Experimental evidence on promotion of electric and improved biomass cookstoves. *Proceedings of the National Academy of Sciences* **116**, 13282–13287 (2019).
18. Das, I. *et al. A virtuous cycle. Reviewing the Evidence on Women's Empowerment and Energy Access, Frameworks, Metrics and Methods*. (2020).
19. Mobarak, A. M. & Saldanha, N. A. Remove barriers to technology adoption for people in poverty. Nat Hum Behav 1–3 (2022) doi:10.1038/s41562-022-01323-9.
20. Kar, A. & Zerriffi, H. From cookstove acquisition to cooking transition: Framing the behavioural aspects of cookstove interventions. Energy Research & Social Science **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. Opening Opportunities, Closing Gaps | ESMAP. https://esmap.org/ESMAP_Opening_Opportunities_Closing_Gaps.
23. Bailis, R., Drigo, R., Ghilardi, A. & Masera, O. The carbon footprint of traditional woodfuels. Nature Clim Change **5**, 266–272 (2015).
24. Fisher, S. *et al.* Air pollution and development in Africa: impacts on health, the economy, and human capital. The Lancet Planetary Health **5**, e681–e688 (2021).
25. Morris, M. D. Factorial Sampling Plans for Preliminary Computational Experiments. Technometrics **33**, 161–174 (1991).
26. Campolongo, F., Cariboni, J. & Saltelli, A. An effective screening design for sensitivity analysis of large models. Environmental Modelling & Software **22**, 1509–1518 (2007).
27. 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).
28. Robinson, L. A., Hammitt, J. K. & O'Keeffe, L. Valuing Mortality Risk Reductions in Global Benefit-Cost Analysis. Journal of Benefit-Cost Analysis **10**, 15–50 (2019).
29. Bruce, N. *et al.* The Government-led initiative for LPG scale-up in Cameroon: Programme development and initial evaluation. Energy for Sustainable Development **46**, 103–110 (2018).
30. Stoner, O. *et al.* Household cooking fuel estimates at global and country level for 1990 to 2030. Nat Commun **12**, 5793 (2021).
31. Burnett, R. T. *et al.* An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. Environmental Health Perspectives **122**, 397–403 (2014).
32. Mansournia, M. A. & Altman, D. G. Population attributable fraction. BMJ **360**, k757 (2018).
33. The Relative Wealth Index. *Facebook Data for Good* https://dataforgood.fb.com/tools/relative-wealth-index/.
34. Hosier, R. H. *Energy use in rural Kenya: household demand and rural transformation*. (Nordiska Afrikainstitutet; The Beijer Institute, 1985).
35. 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).
36. EPA. *Technical Support Document: Social Cost of Carbon, Methane,*. 48 (2021).
37. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. Nature Clim Change **8**, 895–900 (2018).
38. Dagnachew, A. G., Lucas, P. L., van Vuuren, D. P. & Hof, A. F. *Towards universal access to clean cooking solutions in sub-Saharan Africa*.
39. 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).

40. Benefits of action to reduce household air pollution tool. https://www.who.int/tools/benefits-of-action-to-reduce-household-air-pollution-tool.

Figures

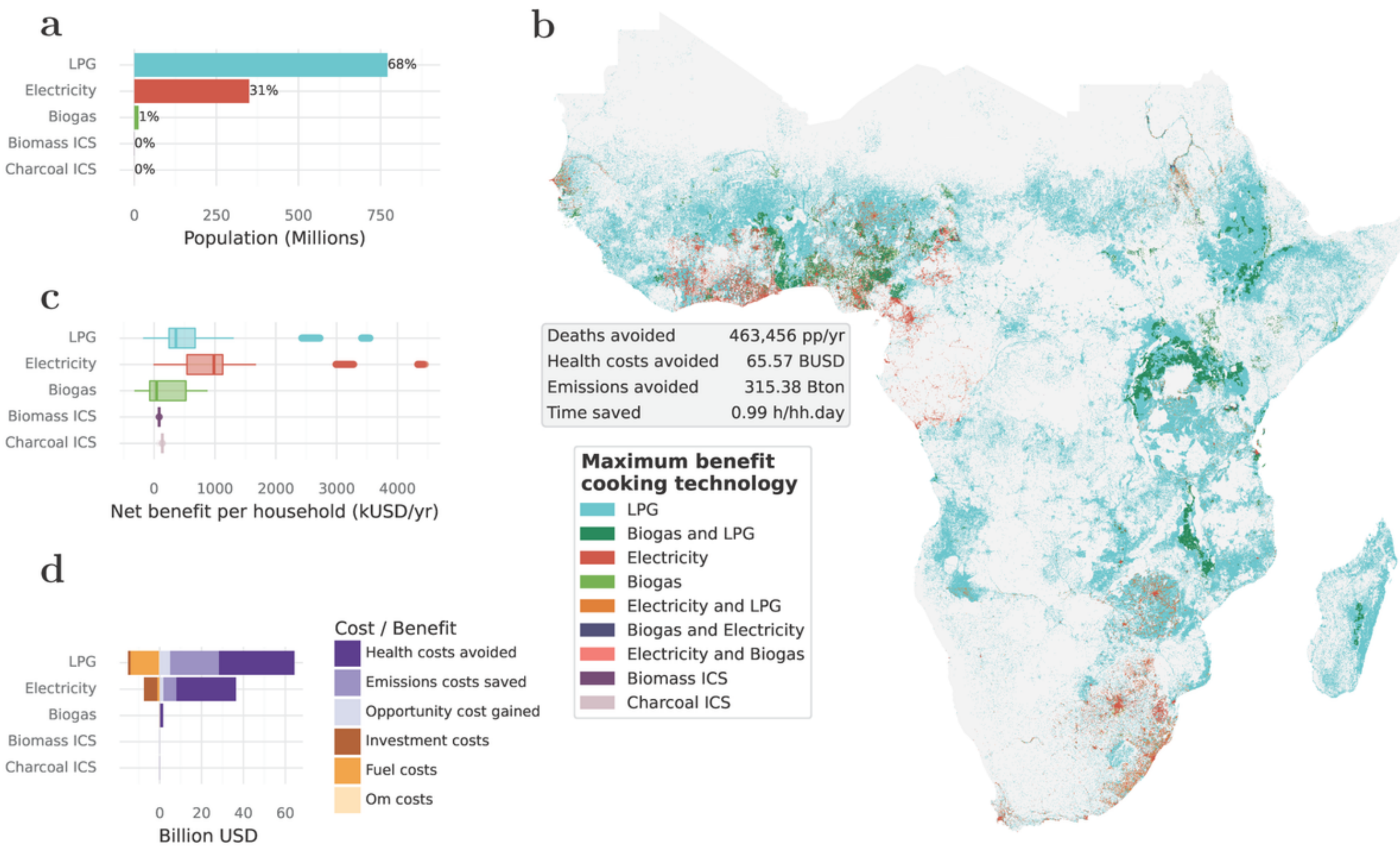

Figure 1

OnStove results from a social net benefits perspective (i.e. including both private benefits and externalities). a) bar-plot indicating the stove- split in the scenario, b) spatial distribution of stoves with the highest net-benefit across SSA, c) box-plot indicating the net-benefit resulting from switching to each stove type and d) total costs and monetized benefits of each stove type, note that salvage costs are incorporated in the investment values (Investment costs = investment – salvage).

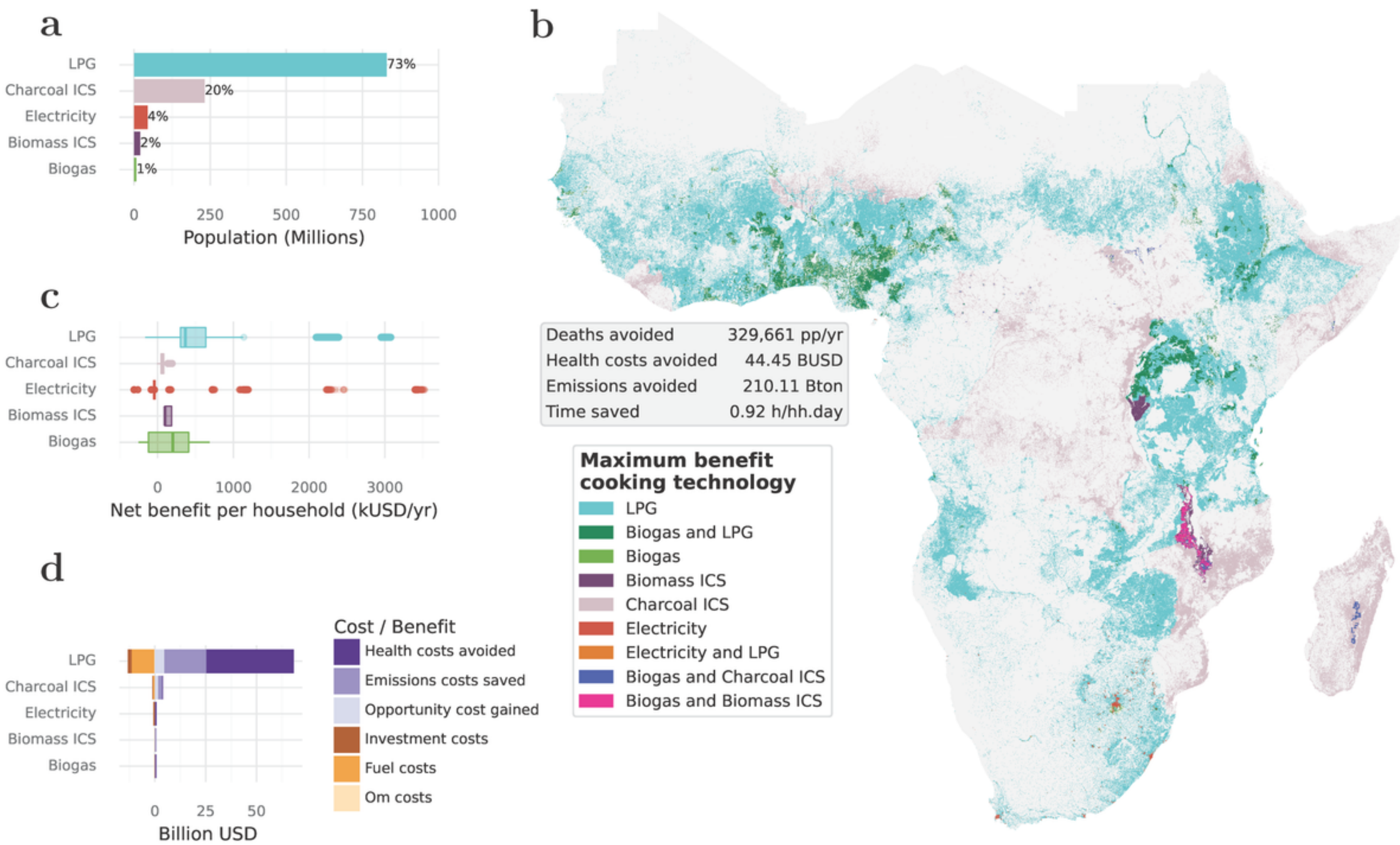

Figure 2

OnStove results omitting social benefits. a) bar-plot indicating the stove-split in the scenario, b) spatial distribution of stoves with the highest net-benefit across SSA, c) box-plot indicating the net-benefit resulting from switching to each stove type and d) total costs and monetized benefits of each stove type, note that salvage costs are incorporated in the investment values (Investment costs = investment – salvage).

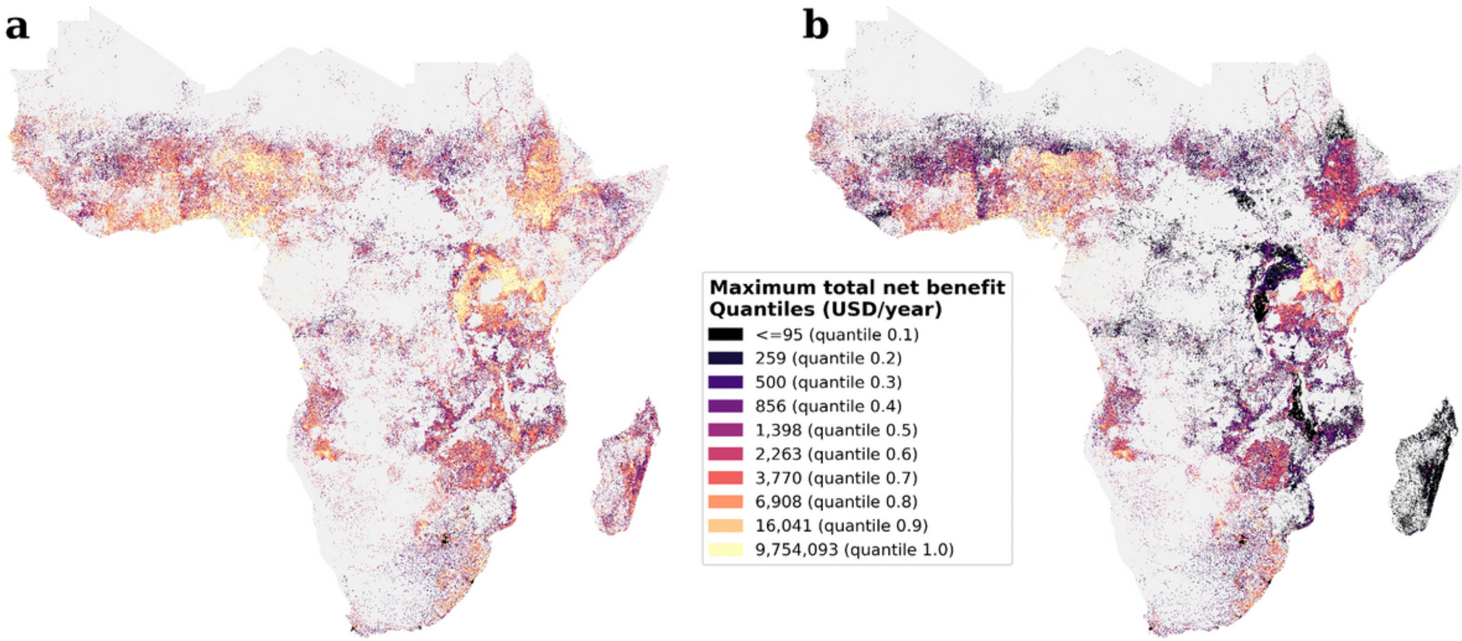

Figure 3

Total net benefit obtained by switching stoves in every square kilometer (USD/yr) from a a) social benefits perspective, b) private benefits perspective.

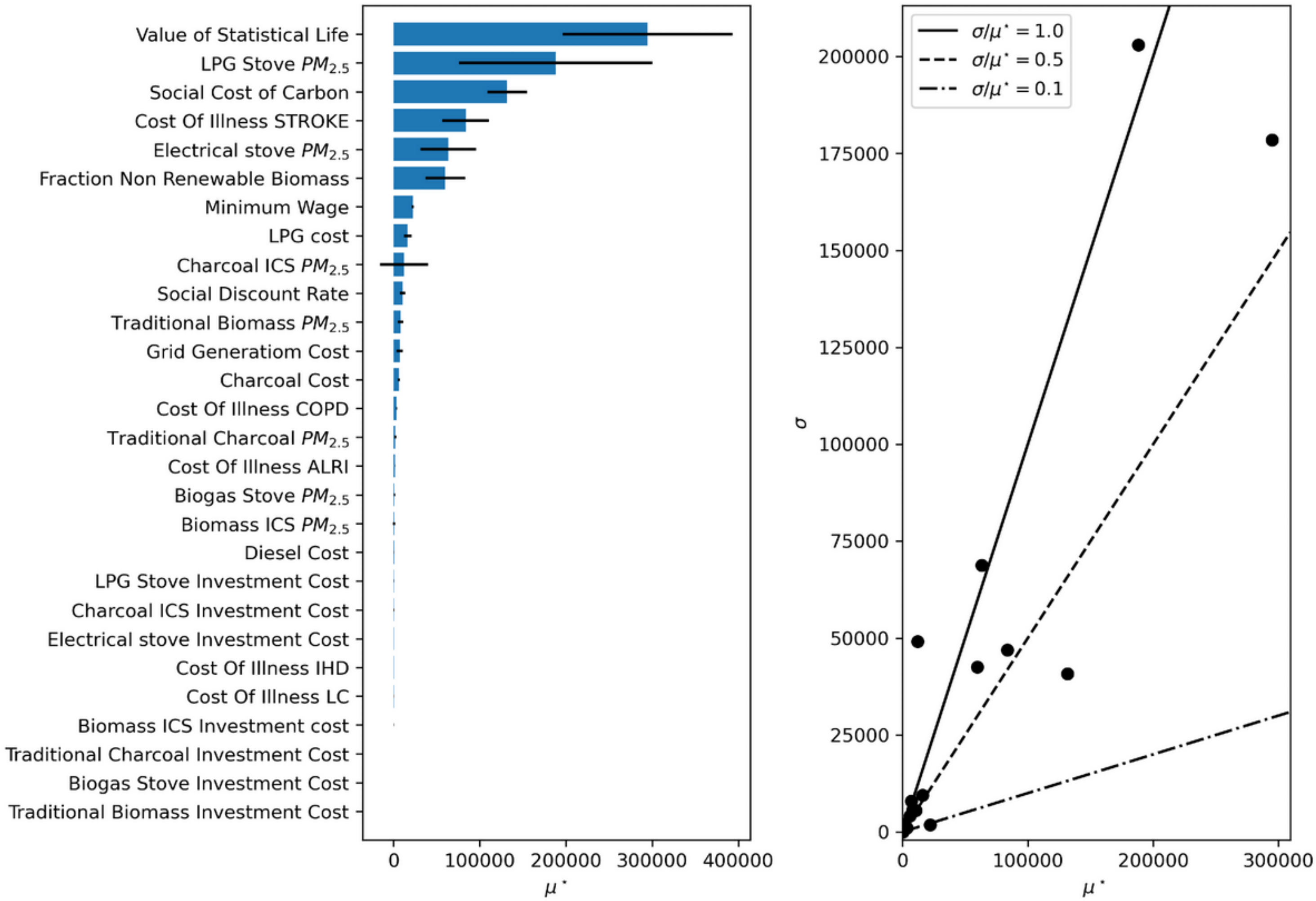

Figure 4

Sensitivity of inputs to the net-benefit equation. μ* is the mean of variation of output given the variation in each input and describes how important each input variable is in relation to the assessed output (higher values for μ* indicates higher impact). σ is the standard deviation of the variation and gives insight into how much each parameter interacts with other parameters

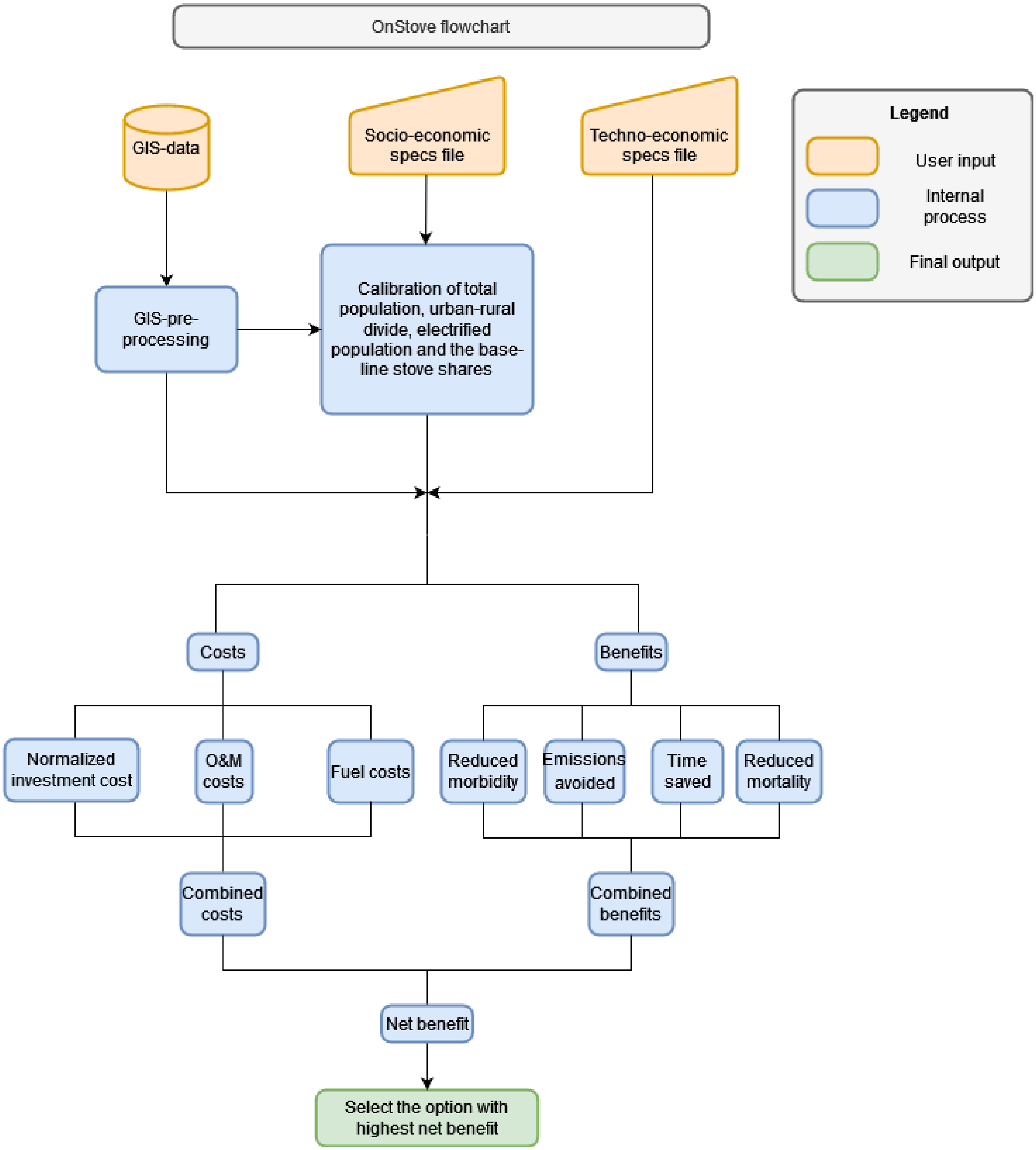

Figure 5

OnStove flowchart.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryfileCResultsofthesensitivityanalysis.docx