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LETTER

The cost of cooking a meal. The case of Nyeri County, Kenya

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Keywords: cooking energy access, levelized cost of cooking a meal (LCCM), Kenya, clean cookstoves, modern cooking

Supplementary material for this article is available online

Abstract

Energy for cooking is considered essential in achieving modern energy access. Despite this, almost three billion people worldwide still use solid fuels to meet their cooking needs. To better support practitioners and policy-makers, this paper presents a new model for comparing cooking solutions and its key output metric: the 'levelized cost of cooking a meal' (LCCM). The model is applied to compare several cooking solutions in the case study area of Nyeri County in Kenya. The cooking access targets are connected to the International Workshop Agreement and Global Tracking Framework's tiers of cooking energy access. Results show how an increased energy access with improved firewood and charcoal cookstoves could reduce both household's LCCMs and the total costs compared to traditional firewood cooking over the modelling period. On the other hand, switching to cleaner cooking solutions, such as LPG- and electricity, would result in higher costs for the end-user highlighting that this transition is not straightforward. The paper also contextualizes the results into the wider socio-economic context. It finds that a tradeoff is present between minimizing costs for households and meeting household priorities, thus maximizing the potential benefits of clean cooking without dismissing the use of biomass altogether.

1. Introduction

Worldwide, 2.9 billion people are estimated to rely primarily on solid fuels for their cooking needs (World Health Organization 2016), mainly located in sub-Saharan Africa and East Asia (figure 1). The number of people without modern cooking solutions is far higher than the number of people without access to electricity (almost 1.2 billion people) (IEA 2016).

There are many reported negative impacts associated with the use of traditional cooking methods. For example, the WHO estimate that there are 4.3 million premature deaths annually as a result of indoor air pollution exposure due to the lack of clean or modern energy services for cooking (World Health Organization 2016). In addition, households cooking with traditional stoves and fuels use considerable parts of their incomes for either purchasing fuels for cooking, or using significant amount of their time for from collecting firewood (IEA and the World Bank 2015). Finally, even though cooking is not considered as the major cause of deforestation[5], where firewood is not collected sustainably both environmental and climate impacts are present.

In this context, the 7th Sustainable Development Goal (SDG) includes the target of ensuring universal access to affordable, reliable and modern energy services by 2030 (United Nations 2015). This includes clean[6] cooking solutions. To achieve this challenging goal, understanding the capital, fuel and health costs of the different cooking solutions is needed for promoting appropriate technological solutions that minimize the final costs for end users. Additionally, that understanding has to be complemented with adoption

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[5] Except in hotspots in certain parts of the world (Foell *et al* 2011).

[6] For the purpose of this paper, the authors use the terminology 'clean' in reference to cooking solutions. This is in line with broader global rhetoric used by organisations such as the International Energy Agency and the Global Alliance for Clean cookstoves. The use of this terminology is interrogated further in a forthcoming publication by the second author (Ray *et al* 2017).

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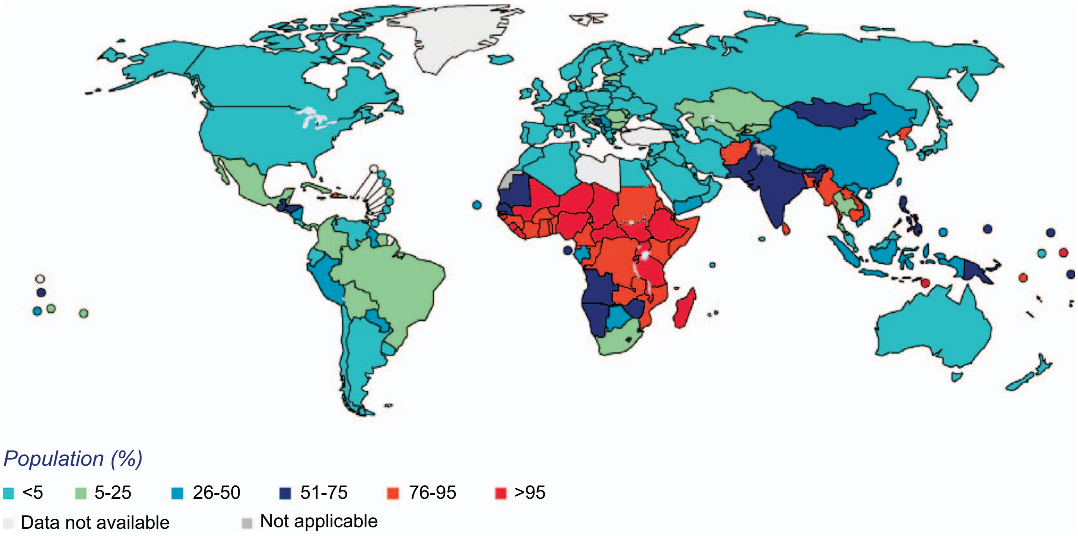

Figure 1. Percentage of population using polluting fuels and technologies for cooking in 2014 (World Health Organization 2016).

strategies that explore non-technical dimensions, such as the local market functioning, and the local policy and behavioral contexts (see annex A for the literature review).

On the first point, there is a lack of easy-adoptable quantitative techno-economic models for comparing cooking solutions within the existing literature. This is in line with (Foell *et al* 2011), which urged for increased research in energy-economic models for cooking energy access and for targeted case studies applying those models. Such models should be simple enough to be widely adoptable, and should be designed to help practitioners for comparing technological solutions and setting goals of cooking energy access. In fact, open-access and simplified models for the optimal allocation of economic resources have the potential to lower the barriers for adoption, and ease repeatability (DeCarolis *et al* 2012).

The selection of cooking solutions will need (a) consistent metrics for setting cooking access targets, (b) easy adoptable cost models to compare technology options and estimate the costs of this transition and (c) an understanding of how broader 'software' dimensions such as socio-economic status, gender and culture influence the household decision making process to purchase stoves and fuels (Ray *et al* 2014) (Sesan 2011).

Thus, this paper specifically focuses on (a) and (b), creating an easy adoptable model to be used by energy practitioners for comparing cooking solutions related to widely adopted metrics. In this paper the 'levelized cost of cooking a meal' (LCCM) is introduced. The model is then applied to the case study of the Nyeri County in Kenya (annex B). A limited but representative number of cooking solutions are compared in the case study. Then (c) is discussed in the final section of the paper, contextualizing the model results into the broader socio-economic context for the adoption of clean cooking solutions.

2. Methods

For this study two leading metrics[7] to measure access to cooking solutions are used in conjunction; the International Organization for Standardization (ISO) standards for cookstoves proposed in the International Workshop Agreement (IWA) (ISO 2012) and the multi-tier Global Tracking Framework (GTF) for cooking energy access (IEA and the World Bank 2015). The two scales are comparable, and the combination of the two is represented in table 1.

A number of cookstoves were chosen to represent all the access tiers/levels within the IWA and GTF cooking access frameworks, both depending on the cooking solutions available and adopted in Nyeri County.

The compared solutions are:

- Firewood-based stoves: traditional three stove open fire (figure 2) and a wood ICS. The ICS used is called the 'Kuni M'Bili[8] (figure 2). These options were compared both in the case in which the firewood is collected or purchased.
- Charcoal-based stoves: traditional stove (Kenyan Jiko) and a charcoal Kuni M'Bili.
- Kerosene cooking stove.
- LPG cooking stove.
- Electrical stove.

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[7] A contextual review of the key metrics for cooking energy access is provided in annex A of the supplementary material.

[8] The Kuni M'Bili is a duel fuel stove using both firewood and charcoal. More information about the stove can be obtained here: (Boulkaid 2014).

Table 1. IWA standard 'tiers' and GTF 'levels' of cooking energy access. Elaboration of the authors from (IEA and the World Bank 2015, ISO 2012)

IWA standard	Global Tracking Framework level	Cookstove and fuel	Thermal Efficiency (%)	Indoor emissions CO (g min^{-1})	Indoor emissions PM$_{2.5}$ (mg min^{-1})	Safety
Tier 0	Level 0 or 1	Self-made cookstove[a]	< 15	> 0.97	> 40	poor
Tier 1	Level 1 or 2	Manufactured non-BLEN cookstove	≥ 15	≤ 0.97	≤ 40	poor
Tier 2	Level 2 or 3		≥ 25	≤ 0.62	≤ 17	fair
Tier 3	Level 3 or 4	BLEN cookstove	≥ 35	≤ 0.49	≤ 8	good
Tier 4	Level 4 or 5		≥ 45	≤ 0.42	≤ 2	best

[a] **BLEN** = refers to cookstoves that use one of the following as fuel: biogas, LPG, electricity or natural gas.

Figure 2. Kuni M'Bili ICS stove (left) and three stone open fire (right), Nyeri County, 2014.

Table 2. IWA tiers and GTF levels of cooking access assessment for compared stoves, elaboration of the authors from field observation and (Kshirsagar and Kalamkar 2014)(Jetter *et al* 2012) (MacCarty *et al* 2010)(Global Alliance for Clean Cookstoves 2016)[9]

Stove type	Cookstove and fuel	Efficiency	Indoor emissions CO	Indoor emissions PM$_{2.5}$	Safety	FINAL IWA TIER	GTF LEVEL
3 stones open fire	0	0	0	0	**0–1**	**0**	**0**
Traditional charcoal stove	1 or 2	2	0	1	**0–1**	**0**	**0–1**
ICS firewood stove	1 or 2	1	1	1	2	**1**	**1–2**
ICS charcoal stove	1 or 2	2	1	1	2	**1**	**1–2**
Kerosene Stove	1 or 2	3	2	3	2	**2**	**2–3**
LPG Stove	3 or 4	4	4	4	3	**3**	**3–4**
Electrical stove	3 or 4	4	4	4	4	**4**	**4–5**

The key techno-economic parameters for the compared stoves are reported in annex D of the supplementary material stacks.iop.org/ERL/12/065007/mmedia.

In table 2, the compared stoves were assessed with the IWA tiers and the GTF levels of access to cooking solutions.

A model was then built to evaluate the costs of reaching different tiers of access to cooking services in the Nyeri County. Data for the model was collected from both the literature review and from field study sites. The cooking patterns of 15 households were observed for a period of one month[10], gathering data regarding the fuel usage and the cooking time per

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[9] In relation to health, the WHO indoor air quality guidelines (2014) find that most of the solid fuel interventions promoted in recent years do not come close to reaching the WHO IT-1 for annual average kitchen PM2.5. Any stove/fuel mix that aims to positively impact on health will need to be tier 3 (LPG) or higher.

[10] About half of the observed household used improved ICS stoves either with wood or charcoal. The other houses mostly used open fires, with a few houses using kerosene stoves as well (stacking). The observations were made by a mix of personal observations (a person in the house while cooking) and semi-structured interviews to households' members and to employees of the local NGO the Help Self Help Centre.

meal. The developed cost model is a deliberately simple[11], open source spreadsheet-based accounting model which takes into account several parameters influencing the cost of cooking. In the model the concept of LCCM is introduced (equation (1)). That is the cost for cooking a 'standard' meal with a certain fuel-technology combination.

$$\begin{aligned}\mathrm{LCCM}_t &= \mathrm{LCCM}_{\mathrm{fuel}} + \mathrm{LCCM}_{\mathrm{stove}} \\ &= \frac{F_{\mathrm{ct}} * E_m}{\eta_s} + \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{Ml}_t}{(1+r)^t}} \qquad (1)\end{aligned}$$

where:

- F_{ct} is the fuel cost in USD/MJ at the time t.
- E_m the final energy required for cooking a meal in MJ.
- η_s the stove efficiency [%].
- I_t is the stove investment cost.
- $O\&M_t$ are the stove operation and maintenance costs.
- Ml_t are the amount of meals cooked in the time unit (1 year).
- n is the stove lifetime [years].
- r is the discount rate [%].

In the formulae above E_m is calculated based on a 'standard meal'[12]. From field observations for the observed households in the Nyeri County a meal for four people, using an improved charcoal cookstove, is cooked on average in approximately 45 min. Considering then:

- Energy content of charcoal : 30 MJ kg^{-1} (Jenkins 1993).
- Stove efficiency of 30%, obtained by standard Water Boiling Test (University Of Nairobi Department Of Chemistry 2013).
- A burning rate of 9 g min^{-1}, obtained by standard Water Boiling Test (University Of Nairobi Department Of Chemistry 2013).

Since we have equation (2)

$$E_m = \mathrm{LHV}_{\mathrm{fuel}} . m_{\mathrm{fuel}} . \eta_{\mathrm{stove}} . \qquad (2)$$

And the fuel burning rate being given by (3)

$$\rho = \frac{m_{\mathrm{fuel}}}{t} . \qquad (3)$$

We get equation (4)

$$E_{\mathrm{meal}} = \mathrm{LHV}_{\mathrm{fuel}} . \rho . t . \eta_{\mathrm{stove}} . \qquad (4)$$

We arrive at the conclusion that one 'standard' meal needs 3.64 MJ of final energy, or 12.15 MJ of primary energy to be cooked. This result is in accordance with the results found in literature (Pokharel 2004). The value of final energy per meal is independent from the used stove-fuel combination. Starting from this value then the primary energy (and fuel usage) were calculated for each stove-fuel combination. The energy needed per meal will be used as a basis for comparing cooking energy access solutions in the model.

The LCCM is then calculated for reaching different targets of energy access with different technological solutions. Additionally the monthly costs for cooking with different technological options are evaluated. For evaluating the value of collected firewood, the opportunity cost of collecting it was used. At the same time, the model permits to evaluate the potential impact of cooking on the local forest. The methodology for estimating the opportunity cost of firewood and the impact of cooking on the local forest is reported in annex C.

Further, the cost model is applied to the whole Nyeri County[13], and several scenarios are evaluated to reach different cooking access targets by 2030. The year 2030 is chosen as final year of the model, in accordance with SDG7 and the Sustainable Energy for All (SE4All) targets. Three scenarios are evaluated:

- *Reference scenario (REF):* in which the cooking patterns in the Nyeri County change accordingly to historical trends until the year 2030.

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[11] The cooking model is deliberately easy to use for it to be transmitted to energy practitioners and policy makers, similarly to the electricity model presented in (Fuso Nerini *et al* 2016b) and the energy for productive uses model in (Fuso Nerini *et al* 2016a). This compares, for instance, to the cooking models used in (Cameron *et al* 2016, IEA 2016, Fuso Nerini *et al* 2015) which use more complex models. (Cameron *et al* 2016) uses a stand-alone cooking fuel demand and choice model that is iterated with a global optimization model. (Fuso Nerini *et al* 2015) uses a local optimization model. The IEA analyses use a complex multi-regional simulation model (the World Energy Model). All of the models above provide valuable insights, but can take considerable time to learn to use, and not all are open source.

[12] This standard meal was used to validate the model with data from the field study. Future work could look at how this might be differentiated for different areas with different cooking patterns, and for representing the different meals of the day. A way to do that could be to characterize each cooked meal in relation to the 'standard meal'. For instance, a long cooked meal could be expressed as two standard meals, and on the other hand a quick meal as half a standard meal. To be noticed however that the time length of cooking a meal will influence the magnitude of the costs presented in this paper, however it does not influence the observed cost dynamics. Finally, health cost could be internalized in future efforts.

[13] On the number of meals per day used in the model: In Kenya as in most parts of the world, people usually eat 3 meals per day. However, it is common that all three are not fully cooked meals, and rather for example fruits for breakfast, with boiled water used to make tea. Another case of a meal that is not cooked is for example to eat leftovers from lunch for dinner. They usually have to be heated, but not fully cooked all over again. This was observed in the selected sites for this study and led to the assumption of a need of 2.5 meals cooked per day, which was made to account for these variations. It is also noteworthy here, that the number of meals per day would need to be re-calculated when the model is repeated to ensure it is using context specific information making results more reliable.

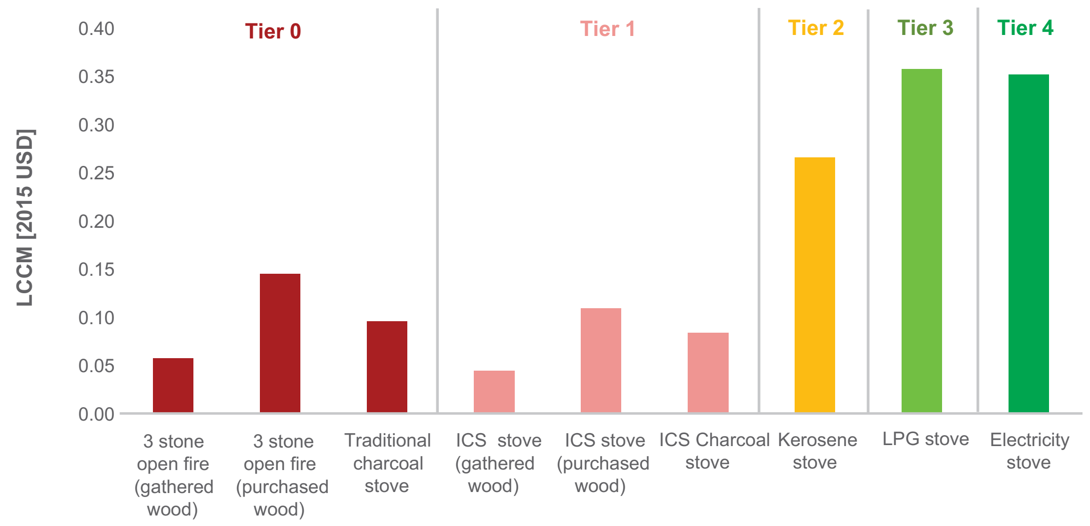

Figure 3. LCCM in the Nyeri County with selected technologies and for reaching different IWA tiers of cooking energy access.

- *Improved cooking scenario (ICSc):* in which a mix of improved cook stoves is adopted in the region gradually by 2030, using non BLEN fuels (equivalent to tiers 1 and 2 in the IWA framework and levels 1–3 in the GTF multi-tier framework).
- *Clean cooking scenario (ClCS):* where only clean cooking is used by 2030 (equivalent to tiers 3 and 4 in the IWA framework and levels 3–5 in the GTF multi-tier framework).

For those scenarios both the costs and the forestry impacts were evaluated. The key model assumptions and scenario technology adoption assumptions are reported in annex D. Finally a sensitivity analysis on key model parameters, such as the potential employment rate in the region, the fuel costs, the stove efficiencies, the cost and lifetime of the stoves and the discount rate was performed. The full results of the sensitivity analysis are reported in annex E.

3. Results

3.1. Levelized cost of cooking a meal and associated costs of cooking for households

When comparing the LCCM of selected technologies a few dynamics can be noticed (figure 3). The first interesting result is that improvements in cooking access can result in cost savings.

In fact, moving from a tier 0 of energy access to a tier 1, or in other words changing from cooking either with a traditional 3 stone fire or charcoal stove to cooking with improved stoves, results in decreased costs for cooking per meal. When looking at tiers 0 and 1 of cooking access, cooking a meal with an ICS stove with the usage of gathered wood is the cheapest option, with a cost of approximately 0.045 US$ per meal. This is almost 25% cheaper than cooking on an open fire with gathered wood[14]. Cooking with an improved charcoal stove is more expensive than cooking with gathered wood. The LCCM of charcoal cooking with an ICS stove is approximately 0.085 US$ and the LCCM of traditional charcoal cooking is approximately 0.095 US$. That is however cheaper (and faster) than cooking with purchased firewood. LCCMs of this last option are over 0.1 US$, with the ICS solutions being approximately 25% cheaper than the open fire solutions. The payback time of adopting ICS solutions varies with the type of input fuel. Switching to an ICS stove when firewood is purchased has a payback time of around 10 months. When firewood is collected the payback time is of around two years. And switching from traditional to ICS charcoal cooking has a payback time of approximately 2.4 years.

Achieving higher tiers of cooking access have considerably higher costs. All the options for achieving tiers 2, 3 and 4 of cooking access have LCCM of over 0.25 US$, with LPG stoves and electricity-based cooking costs per meal of approximately 0.35 US$. Therefore, cooking with higher tier fuels can cost up to eight times more than cooking with ICS stoves that use biomass. Additionally, electricity and LPG networks are not available or not well developed in parts of the Nyeri County, resulting in shortages of supply or purchasing price differences. In other areas of the country, however, different electricity and LPG costs could increase the competitiveness of modern fuel cooking. For instance, a decrease of the current cost of electricity in the county from approximately 0.25 US $/kwh to 0.10 US$/kwh could decrease the LCCM of electrical cooking to 0.14 US$, making it comparable with the 3 stone cooking with purchased wood. Similarly, a decrease in the local LPG costs could increase that option competiveness significantly. This

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[14] See annex C for details on the calculation of the opportunity cost of collecting wood.

Table 3. Yearly cooking costs, fuel usage and forest needed for sustainable cooking for the compared solutions (per household).

	Yearly cooking cost (2015 US$)	Yearly fuel usage	Forest area needed for sustainable use (hectares)
3 stone open fire (gathered wood)	52	1320 Kg	0.33
3 stone open fire (purchased wood)	132	1320 kg	0.33
Traditional charcoal stove	87	2185 Kg of wood equivalent	0.55
ICS stove (gathered wood)	40	970 kg	0.24
ICS stove (purchased wood)	99	970 kg	0.24
ICS charcoal stove	76	1895 Kg of wood equivalent	0.47
Kerosene stove	242	210 kg	–
LPG stove	326	125 kg	–
Electricity stove	321	1318 kWh	–

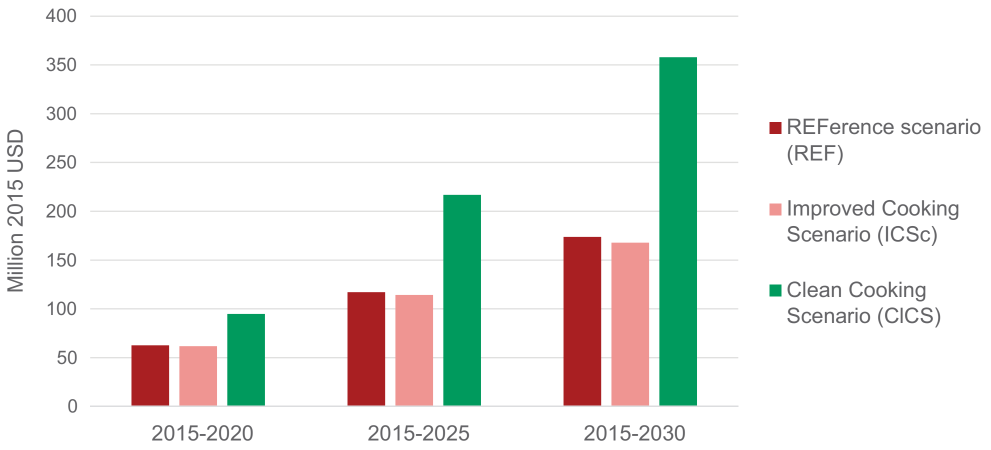

Figure 4. Scenario analysis, annualized cumulative total cooking costs 2015–2030.

result shows the importance of re-calibrating the model for new case studies with local energy prices. This is also noticeable in annex E, which presents a sensitivity analysis of these results to key input parameters.

Looking at the fuelwood usage in table 3 it is possible to notice that traditional charcoal cooking results in the most firewood usage: almost 2200 kg of firewood per household per year. Switching to an ICS charcoal stove would save almost 300 kg of firewood a year. The ICS firewood stove has considerably lower firewood usage, consuming less than 1000 kg of firewood a year. The currently most used cooking solutions, 3 stone open fires, have a firewood usage of approximately 1320 kg of firewood a year per household.

3.2. Nyeri County results

The annualized cumulative costs for the scenario analyzed for the Nyeri County are reported in figure 4.

The improved cooking scenario is the scenario with the overall least-cost in the period 2015–2030 among the ones considered. In this scenario, a mix of improved cookstoves reduces the costs respectively to reference scenario, in which most of the cooking is done by traditional ways in 2030.

In the ICS scenario, the purchase and usage for the whole Nyeri County of improved cooking solutions has a total annualized cost of approximately 165 million US $ over the period 2015–2030. This is approximately 5% cheaper than the reference scenario. Therefore, at the county level, the total costs of improving access to cooking solutions from tiers 0–1 (as highlighted in figure 4) is lower than the total cost of non-action by stakeholders. On the other hand, improving the costs of energy access to a tier 3–4 of energy access in the clean cooking scenario proves costlier. Over 350 million US$ over the period 2015–2030 are needed to provide the Nyeri County's with cooking access with LPG- and electricity-based cooking solutions.

Table 4 reports the wood usage and forest area needed to sustainably support the wood usage in the REF and ICS scenarios in Nyeri County.

In the reference scenario, by 2030, almost 340 kton of wood is needed each year to sustain current cooking practices in the county. To sustainably provide that amount of firewood and charcoal it is estimated that 90% of the available forest in the County would be needed to be allocated only to local cooking practices[15]. Results from the model indicate that the use of clean cooking solutions in the ICS scenario results in lower wood usage and by 2030, the adoption

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[15] It is worthwhile to notice that this value assumes that all the available firewood in the region is dedicated to cooking practices. This is not necessarily true, as other practices compete for wood, such as local manufacturing industry and agriculture. For understanding the sustainability of those practices altogether the model would have to include all biomass-using activities in the region, which is currently out of the scope of the paper.

Table 4. Wood and potential forest usage for the REF and ICS scenario.

	2020		2025		2030	
	REF scenario	ICS scenario	REF scenario	ICS scenario	REF scenario	ICS scenario
% adoption of improved cookstoves	18%	42%	24%	71%	29%	100%
Yearly wood usage (ktones)	252	242	291	268	336	296
Forest area needed for sustaining usage (hectares)	63 276	60 730	73 000	67 182	84 210	74 240
% of total forest in the country needed to support cooking	68%	65%	78%	72%	90%	79%

of improved cookstoves as described in the ICS scenario, would result in up to 40 kton less usage of wood a year.

4. Discussion and wider socio-economic considerations

The model results demonstrate that progressing from tiers 0 to 1 (IWA standard) does show a reduction in costs for households in the long-term. These costs includes both the stove cost (spread over its lifetime) and fuel cost (that could be either purchased or collected). However, although potential cost savings are documented in the literature (The World Bank 2011, Vaccari *et al* 2012, Bhojvaid *et al* 2014, Fuso Nerini *et al* 2015), it does not necessarily translate to adoption or sustained usage of clean cookstoves. As (Hanna *et al* 2012) point out, if 'the widespread belief in the value of the technology is low, can we expect the households to sustain [this] behavior change over time?' The next paragraphs contextualize the results into the broader socio-economic context and discuss selected barriers for the adoption of clean cooking solutions.

One of the first factors to consider is the cost of purchasing stove itself. These initial costs are often high for households and are a persistent barrier within the literature (Rehfuess *et al* 2014). Options to own a stove may include subsidized prices or free allocation, mainly as a result of external interventions but such approaches have previously hindered the sustained use of stoves (Sesan 2015). As a result of increased emphasis on market based models, micro-finance for clean cooking solutions is on the rise, but thus far has been aimed at the stove value chain so enterprises can enter and maintain their position in the market (Simon *et al* 2014). Access to micro-finance for end-users is present but mostly limited to urban areas. High interest rates charged on credit by commercial banks and other lending institutions is a concern. At the same time, the Kenyan government imposes import duty on cookstoves and this combined with other factors such as VAT, poor transport and road infrastructure can increase the cost of a stove by up to 47% (Lambe *et al* 2015).

Given the financial barriers, to encourage adoption there is a need to encourage households to perceive cooking technology as both a technological innovation and a long-term investment to complement everyday household cooking practices. In fact, even if some options may result in monetary savings, private economic costs such as potential health gains, time saved in collecting/purchasing fuel, cooking time, is not always a decisive factor for households, especially when fuel is gathered as a free resource (Jeuland and Pattanayak 2012). This also relates to broader socio-cultural factors relating to the persistent use of traditional cooking technologies which have been largely ignored by donors and policy makers (Ray *et al* 2017). For example, in some of the literature, there are perceptions that traditional cooking solutions cook food faster, are culturally appropriate and can be more durable for the type of cooking needed (Concern Universal 2011).

In addition, where firewood is collected rather than purchased, the payback time of switching to an ICS is around 2 years and therefore the wider socio-cultural benefits of using a traditional cooking technology can potentially outweigh the long-term benefits of purchasing an ICS. These payback costs can be even higher/longer when households transition to a charcoal ICS.

The results from this study highlight the significant increase in costs for households in the Nyeri County to transition from tiers 0–1 (biomass) to higher tier BLEN fuels/technologies. It is important to notice that these costs represent only the final costs for the user of the stove. Health costs, as well as possible pricing for greenhouse gasses, if internalized into these calculations could increase the cost competiveness of clean cooking solutions from a social perspective. Presently, only 0.5% of the national population cooks with electricity in Kenya. On the other hand, according to local surveys (DHS Program 2015), there has been a steady increase in the use of LPG in Kenya. However, in Nyeri County unreliability of LPG supply is a major barrier. Therefore, for a higher uptake of BLEN cooking other measures might be necessary, such as policy support and greater evidence regarding the health gains related to switching to modern fuels.

At the Nyeri County level, the cost analysis suggests that the transition from either a REF or ICSs to a ClCS scenario will be difficult to achieve by 2030 unless significant financial resources are invested into the clean cooking sector together with dedicated policies for the sustained adoption of clean cooking solutions. Finally, our results do suggest that there could be lower usage of surrounding forest areas with increasing tiers of access to cooking solutions. However, whereas previous literature has been quick to blame domestic fuelwood use on deforestation (D'Agostino *et al* 2015), it is practices such as clearing land for agriculture purposes (Crewe 1997) rather than domestic fuelwood use that is a major cause of deforestation (FAO 1997). It is here that this model can be the first step for policy makers and practitioners to identify sustainable forest practices that meet the daily demand for biomass by households: if the local firewood availability is not considered enough for all local uses, improved forestry practices could be considered.

5. Conclusions

The model presented in this paper adds limited but useful insights for estimating costs of achieving different cooking access targets with different technological solutions. When looking at the levelized cost of cooking a meal (LCCM) with different technologies, certain dynamics emerge. Firstly, results show how the adoption of improved wood and charcoal cookstoves, and therefore the first step in increasing access to cleaner cooking access, is already cost-effective. Adopting improved biomass cookstoves results in LCCM up to 25% lower for wood-based solutions, and up to 15% lower for charcoal-based solutions. Furthermore, adopting tier-1 cooking solutions would decrease wood usage and therefore the area of forest needed to support household cooking uses. LCCMs of higher-tier levels of cooking access are currently considerably more expensive. Cooking with electricity or LPG could cost up to 8 times more than cooking with an ICS stove in the Nyeri County. That is also due to the current high costs of electricity and LPG in the region (when LPG and electricity are available). LPG- and electricity- based cooking solutions could however provide significant health benefits. In this context, despite the higher costs, there have been cases where very aggressive policies (usually subsidies-based) made it possible for countries to transition to clean cooking in short times (Kojima 2011).

Finally, for sustainably supporting firewood and charcoal cooking in the Nyeri County, up to 90% of the available forest would be needed. Therefore, in the Nyeri County the available forest could be enough to sustain cooking activities. However, it is the case that in the County several other activities contribute to deforestation.

This paper also discussed that while cost reductions can be seen when moving to higher tiers, there are wider socio-economic factors that affect the adoption of clean cooking solutions. Lower costs are not sufficient to ensure a transition to clean cooking solutions. Therefore, the presented techno-economic model needs to be implemented in conjunction with qualitative methods in order to tease out the socio-economic barriers and enablers to clean cooking solutions.

The research work presented in this paper can be brought forward in several ways. First, the model presented could be enriched with attempts at internalizing other external social and environmental costs, supported by further validation with new case studies. As of now, the LCCM takes into account the direct costs to the end user (including the opportunity cost of collecting firewood). However one key aspect of moving more rapidly away from traditional cooking methods is effectively 'pricing in' all the benefits and costs of different ways of cooking (Toman and Bluffstone 2017). Full social costs of cooking solutions include inconvenience costs, such as higher time consumption and health effects, and environmental impacts, such as forest depletion. Additionally, effects of lack of financing options for purchasing new stoves could be internalized by increasing the discount rates in the model (e.g. using fitted discount rates depending to the household's annual expenditures, as done in (Ekholm *et al* 2010)). Also, the impact of fuel stacking on the model results could be evaluated. Finally, the presented model could be coupled with Geographic Information Systems (GIS) for regional and national case studies.

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