Mitigating Climate Change through Sustainable Technology Adoption: Insights from Cookstove Interventions

Yonas Alem

Working Paper Series: CC-006

Bringing Rigour and Evidence to Economic Policy Making in Africa

AFRICAN ECONOMIC RESEARCH CONSORTIUM
CONSORTIUM POUR LA RECHERCHE ÉCONOMIQUE EN AFRIQUE

Mitigating Climate Change through Sustainable Technology Adoption: Insights from Cookstove Interventions

By

Yonas Alem
School of Business, Economics and Law
University of Gothenburg, Sweden

AERC Working Paper Series: CC-006
African Economic Research Consortium, Nairobi
September 2021

THIS RESEARCH STUDY was supported by a grant from the African Economic Research Consortium. The findings, opinions and recommendations are those of the author, however, and do not necessarily reflect the views of the Consortium, its individual members or the AERC Secretariat.

Published by: The African Economic Research Consortium
P.O. Box 62882 - City Square
Nairobi 00200, Kenya

Contents

List of tables

List of abbreviations and acronyms

AERC	Africa Economic Research Consortium
BDM	Becker-DeGroote-Marchak
CIFOR	Centre for International Forestry Research
CO2	Carbon Dioxide
DID	Difference-in-Differences
EfD	Environment for Development
FAO	Food and Agricultural Organization
ICS	Improved Cookstove
IPCC	Intergovernmental Panel on Climate Change
IRGC	International Risk Governance Council
LPG	Liquefied Petroleum Gas
MT	Metric Tonnes
NGOs	Non-Government Organizations
OLS	Ordinary Least Square
PSM	Propensity Score Matching
RCTs	Randomized Controlled Trials
RD	Regression Discontinuity
SIDA	Swedish International Development Cooperation Agency
SSA	Sub-Saharan Africa
SSC	Social Cost of Carbon
UNECA	United Nations Economic Commission for Africa
USEPA	United States Environmental Protection Agency
WHO	World Health Organization
WTP	Willingness-to-Pay

Abstract

Deforestation and burning of forest products to meet cooking needs massively contribute to global warming. In order to reduce the biomass fuel consumption of households in developing countries, various improved cookstove (ICS) interventions were implemented by governments, Non-Government Organizations (NGOs), and other stakeholders in the past decades. This paper synthesizes the impact evaluation literature on the adoption and impact of ICS, and their role in improving household welfare, while reducing the pressure on forest resources and mitigating emission of carbon dioxide (CO2). The paper points out five important knowledge gaps, which future research may address. First, more research is needed on the effectiveness of different mechanisms that address liquidity constraints, such as stove-for-work programmes, which some research has already shown are effective in relaxing households' liquidity constraints to adopt ICS. Second, in order to improve reliability of estimates of the impact of ICS, studies should be guided by proper impact evaluation protocols, such as determining sample size using statistical power analysis. Third, more research is needed on the effects of ICS beyond fuel and time saving, such as time allocation and wellbeing of women. Fourth, urban households are under-represented in stove studies, but more studies on urban households are needed, because they consume substantial amounts of biomass fuel, most importantly charcoal. Finally, and most importantly, all existing stove studies exclusively focus on households. Micro, small and medium-scale enterprises in Africa consume nearly half of the biomass fuel consumed in the continent. Experimental work on firm energy use behaviour and transition to cleaner sources is urgently needed. Otherwise, reduction in biomass fuel use by households may be compensated by increased biomass use by firms.

Key words: *Biomass fuel; Improved cookstoves; RCTs; Causal impact.*

JEL classification codes: *C21; C93; D13; H23; O13; O33; Q23.*

Acknowledgements

I thank Njuguna Ndung'u, Marc Jeuland, Rashid Hassan, Konstantin Makrelov, Maximiliane Sievert, Wilson Wasike, Abebe Shimeles, Finn Tarp, participants at the Climate Change and Economic Development in Africa Project Inception Workshop (Nairobi, Kenya) and Mid-review Workshop for Framework Research (virtual), and participants at the 14th Environment for Development (EfD) annual meeting (virtual) for helpful comments and suggestions. Financial support from the African Economic Research Consortium (AERC) and the Swedish International Development Cooperation Agency (Sida) through EfD is gratefully acknowledged. All errors and omissions are mine.

1. Introduction

Climate change is already resulting in extreme weather events, changing precipitation, sea-level rise, high risk of extinction of marine species, and declining agricultural yield in many regions of the world (IPCC, 2014). Because of its heavy reliance on agriculture, sub-Saharan Africa is being affected disproportionately by climate change compared to other regions (Serdeczny et al., 2017). Carbon dioxide (CO_2) emission, mostly from deforestation, constitute the second largest source of carbon emissions after combustion of fossil fuels, contributing significantly to global warming and climate change (Jayachandran et al., 2017).[1] The problem is further exacerbated by the exclusive reliance of over three billion people on solid fuels, which largely constitute biomass fuels, to meet their cooking and heating needs (WHO, 2018). In order to tackle the problem caused by biomass energy use, reduction of biomass use, along with transition to cleaner energy sources, is urgently needed. Since the great oil shock of the 1970s, several improved stove interventions have been rolled out in developing countries to reduce biomass fuel consumption and the pressure on forest and woodland resources (Barnes et al., 1993). This paper reviews and synthesizes the findings from rigorous stove impact evaluation studies, in order to guide policy makers on how to speed up energy transition, and to reduce the pressure on forest resources in developing countries.

The climatic, environmental, and health impacts of biomass fuel use are immense. When forests and woodlands are cut and burned to meet cooking needs, often in inefficient cookstoves, they emit harmful greenhouse gases, such as CO_2, methane, and black carbon (Sagar & Kartha, 2007; Kandlikar et al., 2009; Grieshop et al., 2011). This in turn traps heat and warms the planet, leading to climate change and its associated devastating consequences.[2] Production of biomass fuel to meet cooking needs has been one of the major causes of deforestation and degradation of forests and woodlands (Campbell et al., 2007; Mercer et al., 2012), which destroys invaluable biodiversity and irreversibly degrades local ecosystems (Allen & Barnes, 1985; Geist & Lambin, 2002; Hofstad et al., 2009; Köhlin et al., 2011). At the household level, biomass fuel burned in inefficient cookstoves results in indoor air pollution, which is responsible for 3.3% of the global burden of disease, especially that of women and children, and kills about 3.8 million people per year prematurely (WHO, 2018).[3] In many developing regions, including sub-Saharan Africa (SSA), biomass fuel use also negatively affects the wellbeing of women and children, who bear the main responsibility for collecting fuel (World Bank, 2011) and perpetuates energy poverty (Modi et al., 2005; Sovacool, 2012; Alem & Demeke, 2020).

This paper carefully reviews around 18 studies which investigate the factors that promote adoption of ICS and their impact on various outcome variables using proper impact evaluation methods, including randomized controlled trials (RCTs) and quasi-experimental methods (difference-in-differences, instrumental variables, and regression discontinuity designs).[4] We focus on studies using these methods due to their ability to establish causal relationships and offer insightful policy inputs. The review suggests that, the key driver of adoption of appropriately designed ICS is liquidity constraint. Households in poor communities lack the financial resources to pay the upfront cost of ICS. Social cost-benefit analysis that compares the costs and the benefits of ICS to the society at large suggest that subsidizing (even fully) ICS offers large benefits. Given that forest resources sequester valuable carbon, they have a global good nature. Channelling resources to support the production and dissemination of ICS is therefore cost-effective. Results also robustly show that, empowering women, who are often responsible for cooking and fuelwood collection, but lack the decision-making autonomy to make purchase decisions, is crucial for uptake of ICS. Once adoption constraints are addressed, for households to consistently use ICS, the stoves should meet their cooking needs, and should be easy to transport, install, clean, and maintain. If these conditions are met, households use ICS consistently and reduce their biomass fuel use, and, as a result, the pressure on biomass resources.

The paper points out five important knowledge gaps, which future research may address. First, given the robustly documented role of liquidity constraints, and the debate on whether or not ICS should be distributed free of charge, more research is needed on the effectiveness of different mechanisms, such as stove-for-work programmes, which some research has already shown are effective. Second, in order to improve reliability of estimates of the impact of ICS, studies should be guided by proper impact evaluation protocols, such as determining sample size using statistical power analysis. Third, much of the literature on the impact of ICS focuses on fuelwood consumption, indoor air pollution, and health. More research is needed on the effects beyond fuel and time saving, such as time allocation and wellbeing of women. Fourth, urban households are under-represented in stove studies, but more studies on urban households are needed, because they consume a substantial amount of biomass fuel, most notably charcoal. Finally, and most importantly, all existing stove studies exclusively focus on households. Micro, small and medium-scale enterprises in Africa consume nearly half of the biomass fuel consumed in the continent. Experimental work on firm energy use behaviour and transition to cleaner sources is urgently needed. Otherwise, reduction in biomass fuel use by households may be compensated by increased use by firms.

The paper develops all these points gradually. In Section 2, we lay out the motivation for the focus on experimental and quasi-experimental stove studies. Section 3 reviews the evidence on the factors that promote adoption of ICS and their impact on households and the environment. This section also presents a social cost-benefit analysis of ICS. Section 4 points out the missing links in the experimental stove and energy choice literature. Section 5 concludes the paper.[7]

2. Survey methodology

This review paper systematically explores the factors that promote adoption of improved and modern cookstoves and their impact on biomass fuel use by drawing on studies using credible impact evaluation methods, which include randomized controlled trials, difference-in-differences, regression discontinuity designs, and instrumental variables methods.[5,6] Impact evaluation is a quantitative assessment of how the programme under consideration affects the outcome variables of interest, and, consequently, the welfare of programme participants. The key challenge of any impact evaluation initiative is finding the counterfactual outcome of programme participants, had they not participated in the programme (Khandker et al., 2010).

Assume the researcher is interested in measuring the impact of a certain intervention (say an improved cookstove intervention) and specifies the following regression equation:

$$y_{ijt} = \alpha + \gamma Treatment_j + \beta X_{ijt} + \varepsilon_{ijt} \quad (1)$$

where, y_{ijt} is the outcome variable of interest, biomass fuel consumption by household *i* in village *j* at time *t; Treatment* is a binary indicator for the treatment (i.e., if the household received an improved cookstove); X_{ijt} are control variables; ε_{ijt} is an idiosyncratic random error term that is allowed to be clustered by village *j*; and γ is the coefficient of interest, which measures the impact of the improved cookstove intervention. In order for the standard ordinary least square (OLS) estimator of γ to be an unbiased estimator of the programme effect, the Gauss-Markov assumptions (Verbeek, 2017) require that $E(Treatment_i \varepsilon_{ijt}) = 0$, i.e., there should be no correlation between the treatment variable and the idiosyncratic error term. Assume that improved cookstoves become available to a certain community and some households adopt the stoves while others do not. Estimation of an OLS equation of the outcome variables of interest using the sample of adopter and non-adopter households results in a clear violation of the Guass-Markov assumption, because the two groups of households will likely be systematically different in both observable and unobservable characteristics. Consequently, $E(Treatment_j \varepsilon_{ijt}) = 0$. The programme effect γ will therefore be biased and will not be useful to policy makers.

The programme effect will be unbiased if the ICS were distributed randomly following a randomized controlled trial (RCT) design. RCT is a research method in which programme participants are selected in a purely random manner, i.e., by chance alone, to receive the treatment. Because programme participants are selected by chance (i.e., they did not select themselves into the programme), the group of households that did not receive the treatment can serve as a valid counterfactual group (the control group) for the group that received the treatment (the treatment group) (Duflo et al., 2007).

In some instances where RCTs are not feasible, quasi-experimental methods can be used to identify programme impacts. Three of the reliable and widely used quasi-experimental methods are the difference-in-differences (DID), instrumental variables, and regression discontinuity methods. The DID is a special case of panel data methods, which is applicable when there are at least two rounds of data for the treatment and control groups, one round before the intervention (at baseline) and another round after the intervention (at follow-up). Unlike the RCT method, which is a single-difference estimator, DID takes the difference of the differences, and, consequently, is also known as the double-difference method (Khandker et al., 2010). DID is a reliable estimator because it enables the researcher to control for both observable and unobservable characteristics that play a role in programme enrolment, and thereby identify the programme effects.

If a credible instrumental variable is available, the effect of a programme can also be identified using an instrumental variables estimation method from observational data. An instrumental variable (IV) is an exogenous variable identified to influence the selection into treatment by the treatment group (Khandker et al., 2010; Verbeek, 2017). An appropriate (valid) IV should meet two conditions: instrument relevance, which requires that the IV should be significantly correlated with the endogenous variable (the programme participation variable), and instrument exogeneity, which requires that the IV cannot be an explanatory variable for the dependent variable, i.e., it should not be correlated with the error term of the regression model. The key challenge in instrumental variables estimation is finding a credible instrument that passes the validity requirement (exogeneity and relevance).

Finally, the Regression Discontinuity (RD) method makes use of the discontinuities in the implementation of the programme due to eligibility criteria or some other exogenous factors, and computes the programme impact as the difference in the outcome variable of those above and below the eligibility cut-off point (Khandker et al., 2010). The eligibility criterion could, for example, be economic status as measured by land size or the number of cattle owned for a stove intervention, the administrative border for a land titling intervention, or age for a pension reform. The method relies on the assumption that those around the neighbourhood of the cut-off point (i.e., slightly above and below) are similar in socioeconomic characteristics, an assumption which can be checked, with varying bandwidth.

3. Adoption and impact of improved cookstoves

Factors promoting adoption

Improved cookstove initiatives began receiving attention by international donors, NGOs, and government agencies in the 1970s when the pressure on forest and woody biomass resources started to increase following the great oil shocks (Barnes et al., 1993). Since then, several major improved cookstove programmes have been implemented in various countries, and several studies attempted to measure their impact.[8] However, until recently, most of the improved cookstove programmes implemented in developing countries did not follow a research design that would allow the researcher to establish causal relationships. One key reason is that policy makers and donors often do not find it fair to distribute new technologies such as ICS randomly rather than distributing them only to those who need it or to those who could not afford it (Khandker et al., 2010). Consequently, it is only recently that researchers, governments, donors, and NGOs have begun to distribute ICS following standard impact evaluation designs that allow establishing causal relationships between stove adoption and outcome variables of interest. The current and the next subsection of this paper are devoted to reviewing these studies and synthesizing the factors that drive adoption of ICS and their impact, with a particular focus on fuel use, deforestation and emission of CO_2.

One of the early studies that involved distribution of ICS in a randomized control trial setup was conducted by Mobarak et al. (2012). These authors attempt to answer the classic technology adoption question in development economics in general (Feder et al., 1985) and the economics of ICS adoption in particular: why have adoption rates been poor in developing countries? In 58 villages of two ecologically diverse rural districts of Bangladesh, Jamalpur and Hatia, Mobarak et al. (2012) offered households either a health-improving “chimney stove” or a budget-saving “efficiency” stove at randomly assigned price points (free or positive price). They also conducted a complementary stated preference survey to elicit women’s ICS preferences and perceptions about indoor air pollution and how they value cookstoves in comparison to other basic household developmental needs. Results from the randomized control trial reveal that adoption rate at full market price (US$11 for chimney stove and US$5.80 for efficiency stove) is extremely low—5% for efficiency ICS and 2% for chimney stove types. Most likely due to liquidity constraints, a large proportion of households changed their mind about buying the stoves after ordering them. According to the authors, this suggests that prices are a significant factor that hinder adoption, because households are poor and have other priorities. Traditional stoves, despite their negative attributes, do not cost money to poor households. Results from stated preference surveys suggest that, despite awareness of the negative health impact of traditional stoves, women in rural Bangladesh do not seem to prioritize ICS over other basic developmental needs. Mobarak et al. (2012) conclude that information campaigns are very important to increase adoption of ICS to optimal levels, but they should be combined with policies that address the liquidity constraints of households.

Attempting to shed more light on the reasons for the low adoption rate of ICS, Miller and Mobarak (2013) draw on the experimental part of a companion study, Mobarak et al. (2012). The authors hypothesize the gender difference in preference within households and the lack of autonomy by women to make adoption decisions as the primary reason. In most developing countries, women are the default cooks of the household and are responsible for fuelwood collection, significantly more than men (World Bank, 2011).[9] Consequently, women are very likely to value ICS more than men, who are the default heads of households with the autonomy to make purchase decisions. Experimental results in Miller and Mobarak (2013) suggest that, women reveal a preference for any improved stove (for health-saving stoves in particular) when stoves are offered for free. However, when a small price is charged for any of the stoves, women become less likely than men to adopt the ICS. This clearly signals their lack of decision-making power to make the purchase. The study concludes that, incorporating attributes that are valued by men into ICS will very likely result in higher adoption rates.

Levine et al. (2018) use a randomized control trial in Uganda and investigate the role of imperfect information on attributes of improved cookstoves—an important factor that interacts with liquidity constraint and hinders uptake. The authors offer two types of ICS, fuel-efficient charcoal stoves to urban households and fuel-efficient wood stoves to rural households, at local market prices, experimentally varying the terms of the sales offer. In urban areas, they implement four types of sales contracts: a cash-and-carry offer (standard retail sales), a one week free trial, which includes full payment or returning the cookstove, buying the stoves on credit payable with four equal instalments over four weeks, and a one week free trial followed by time payments. They find that combining a one week free trial with payment for the stove in four instalments results in the highest uptake of the stove (46%), allowing a one week free trial and charging the full payment led to the second highest uptake (29%), repayment in four equal instalment led to 26% uptake, and the standard cash-and-carry results in the lowest rate of uptake (4%). In rural areas where they implemented two kinds of sales contracts, they find free trial with time payments result in 57% uptake, and a cash-and-carry offer had only 5% uptake. Levine et al. (2018) conclude that, if information and liquidity constraints are addressed, the high start-up cost of new cookstoves does not necessarily lead to low demand.

Building on Miller and Mobarak (2013), Alem et al. (2018) offer robust insights on the effects and the magnitudes of difference in preference and decision-making autonomy within the household on willingness-to-pay (WTP) for ICS. They also demonstrate the impact of empowering women on WTP for ICS. The authors create income-earning job opportunities for 360 randomly selected wives, husbands, and couples in six rural villages of the Tigray region of Ethiopia and offer them ICS for sale. The ICS the authors use, known as "Mirt" stove, reduces fuelwood consumption by 50%, protects the cook from flames, and reduces smoke and indoor air pollution by 90%.[10] It cost about US$7.5 at the time of the field work. They use the Becker-DeGroote-Marchak (BDM) method proposed by Becker et al. (1964) to elicit WTP of their subjects. BDM is an incentive-compatible method of eliciting WTP because subjects make real trade-offs when they make decisions (Hoffman, 2009; Alem & Dugoua, 2021; Lusk et al., 2001). After earning income, subjects were randomly assigned to five treatment groups: i) wives invited alone and would make the stove purchase decision alone using the income they had earned individually (Treatment 1 or T1); ii) husbands invited alone and would make the stove purchase decision alone using the income they had earned individually (T2); iii) wives who were invited with their husbands and would make the stove purchase decision alone using the income the couple had earned (T3); iv) husbands who were invited with their wives and would make the stove purchase decision alone using the income the couple had earned (T4); and v) couples who would make the stove purchase decision jointly using the income the couple had earned (T5).

Alem et al. (2018) shows that, the median WTP for ICS is only 41.3% of the market price of the stove. Such a low overall WTP is revealed when all subjects had the ability to pay the full cost of the stove using the income they earned from the public work the authors created. Experimental results suggest that wives, who by default are the household cooks and are responsible for fuelwood collection, are willing to pay 57% more than husbands and 39% more than couples (T5). Wives who were randomly assigned to earn their own income alone and make the stove purchase decision alone (T1) are willing to pay 67% more than husbands who earned their income alone and made the stove purchase decision alone (T2). Alem et al. (2018) show that the average WTP by couples who earned income together and made the stove purchase decision together (T5) is closer to the average WTP by husbands who made the stove purchase decision alone (T2). This clearly indicates the dominance of husbands in joint spousal decisions. They also show that wives who have non-autocratic husbands, i.e., husbands who allow wives to make decisions regarding purchase of their own personal items, are willing to pay 33.6% more than wives with autocratic and moderately autocratic husbands.[11] The authors conclude that policies to promote new technologies, such as ICS, should consider the intra-household difference in division of labour (which likely shapes preferences) and decision-making autonomy. Drawing on their successful work-for-stove programme, Alem et al. (2018) conclude that simple income generating opportunities empower women and improve their decision-making ability and WTP for new technologies.

The development economics literature robustly documents the role of communication and social-learning through peers and social networks in promoting adoption and diffusion of modern technologies (Foster & Rosenzweig, 1995; Bardhan & Udry, 1999; Bandiera & Rasul, 2006; Conley & Udry, 2010; Oster & Thornton, 2012; Jain & Kapoor, 2015; BenYishay & Mobarak, 2019; Alem & Dugoua, 2021). Building on this literature, Miller and Mobarak (2014) draw on the randomized controlled trial conducted by Mobarak et al. (2012) and Miller and Mobarak (2013) and investigate whether learning through opinion leaders and social networks influences demand for ICS. They conduct their study in two stages. In the first stage, they publicize whether or not locally identified opinion leaders chose to order ICS, and investigate how households' adoption decisions respond to this information. In the second stage, they conduct a marketing intervention and study how subsequent adoption choices by other households vary by their social ties to the households in the first stage. The results suggest that opinion leadership and social networks are indeed important, but they are more influential when the advantages and disadvantages of a technology are not easily observed or understood by the household. Their impact also diminishes over time with user experience. The study also documents that negative information is much more noticeable than positive information in social learning. In conclusion, Miller and Mobarak (2014) argue that, the impact of persuasion methods (often used in marketing and psychology) on adoption decision of ICS is likely to be temporary. For sustained adoption and use, they propose that new technologies should be consistent with local preferences and attributes.

A related randomized controlled trial on the effectiveness of the different forms of marketing messages and relaxing liquidity constraints on WTP for ICS was conducted by Beltramo et al. (2015) in the southwestern region of Mbarara, Uganda. These authors provide two types of information on the benefits of ICS: the health benefits, and saving time and money. In order to test the impact of relaxing households' liquidity constraints, they offered ICS on credit, which was to be paid back in four weeks in four instalments. They find that marketing messages do not have a statistically significant effect on WTP, but the option to pay over four weeks greatly increased WTP. Relative to the comparison group (households that were required to pay the cost of the stove in a week's time), those who were offered the opportunity to pay in four instalments spanning four weeks were willing to pay 40% more. The study offers one of the early examples of the possible impact of micro-credit options in boosting WTP for ICS by households.

A comprehensive study that attempts to provide insights on both the demand- and supply-side drivers of adoption of ICS was conducted by Pattanayak et al. (2019). In 100 communities of the Indian Himalayas comprising 1,000 households, they offered both ICS and electric stoves at randomly offered rebates (subsidies) of different levels and measured their impact 18 months later. The supply-side intervention includes acquiring and transporting ICS from urban wholesalers and implementing a marketing, storage, maintenance, training, home delivery, and demonstration of the stoves. Consistent with previous studies, they find liquidity constraint as an important driver of adoption. There is a high level of purchase of ICS at higher rebate prices. Households also use the ICS, but use declined over time due to stove malfunctioning and lack of maintenance. Consequently, households kept on using their traditional stoves as well. The authors conclude that subsidizing ICS is indeed important to promote adoption, but to be effective, subsidies should be combined with effective marketing campaigns and robust supply chains.

Existing experimental studies on both the drivers of adoption of stoves and their impact almost exclusively focus on improved biomass cookstoves. The only exception is Pattanayak et al. (2019) which involved distribution of both improved cookstoves and electric stoves. The distinction between improved cookstoves and modern cookstoves (e.g., electricity and Liquefied Petroleum Gas - LPG) is quite important, because improved cookstoves are designed to reduce biomass fuel use, while modern cookstoves are designed to reduce biomass fuel use to zero and rely on clean energy sources. They are also much more costly than improved biomass cookstoves. In fact, drawing on observational data from urban households, Edwards and Langpap (2005) in Guatemala, and Alem et al. (2014) in Ethiopia argue that, the high start-up cost of modern cooking appliances such as LPG and electric stoves is the key reason for the low energy transition in developing countries.

In order to identify the extent of the impact of the high start-up cost of modern and costly cooking appliances, Alem and Ruhinduka (2020) collaborated with a reputable local micro-finance institution and conducted a large-scale randomized control trial in urban Tanzania involving 16 clusters (sub-wards) and 722 households. They offered two-burner LPG stoves at a market price of US$110 to the treatment groups through subsidy (75%) and on credit, which was to be paid back in six months with three randomly determined repayment options (payback daily, payback weekly, and payback monthly through mobile money transfer).[12] The authors then measure the impact of the LPG stoves on charcoal consumption, deforestation and emission of CO_2, and cooking time four months and 16 months after the interventions. The proportion of households that acquired the LPG stoves in both the subsidy and credit treatment groups is around 70%, whereas in the control group (the group that was offered the LPG stoves at full market price), it is zero. Alem and Ruhinduka (2020) also show that households in the payback daily group paid a larger proportion (91.1%) of the cost of the stove than those in the payback monthly group (86.6%). The authors argue that liquidity constraint is the key reason for the low adoption rate of modern cookstoves, and micro-credit options that offer convenient repayment schedules to households would be extremely useful in facilitating transition to modern cooking appliances.

More recently, Berkouwer and Dean (2020) conducted a randomized controlled trial in urban Kenya and offer insightful explanations for the low WTP and adoption rate of modern household technologies in general, and energy-efficient cookstoves in particular. The authors report that the WTP for the energy-efficient charcoal stove, known as the “Jikokoa” stove in Nairobi, is significantly lower than its market value, although the reduction in yearly charcoal expenditure is equivalent to three times the market value of the stove. Using experimental data from 1,000 households, Berkouwer and Dean (2020) show that offering households a three-month credit period increases WTP by 104% compared to the control group, clearly indicating that credit constraint hinders adoption of new cost-effective technologies. Households in urban Kenya seem to be aware of the benefits of the stove. Unlike previous studies, however, the authors argue that about a third of the impact of access to credit can be explained by inattention to future loan payments. The key policy implication that comes out of Berkouwer and Dean (2020) is in line with Alem and Ruhinduka (2020), i.e., provision of credit or subsidy options would allow households in developing countries to adopt high-return energy-efficient technologies and improve their welfare.

Most of the experimental studies investigating the factors that promote adoption of ICS spell out affordability and propose credit and subsidy programmes to encourage uptake. The key question is whether offering ICS for free negatively affects future WTP, due to reference dependence—a situation whereby consumers anchor their future WTP to prices they paid previously (Közegi & Rabin, 2006). Bensch and Peters (2020) attempt to answer this question by eliciting WTP from rural households in Senegal, some of whom received ICS for free six years earlier in a randomized controlled trial setup. In addition, they elicit WTP from the control group and a group of new households (a new control group). They show that distributing ICS for free does not necessarily lead to a significant decline in WTP in the long run. Their point estimate suggests only 8-15% decline in WTP in the worst case. They also find significant social learning by the control group from the treatment group. Bensch and Peters (2020) conclude that, learning about the technology compensates for a large part of the reference dependence, and free distribution does not lead to decline in future demand.

Impact on households and the environment

Rigorous impacts evaluation of new technologies in general, and cookstove technologies in particular, is of high importance to policy makers, donors, and all other stakeholders. New technologies may not have the desired (or laboratory confirmed) impacts on households (Hanna et al., 2016), or may have other unanticipated impacts, both negative (McLean et al., 2014) and positive (Alem & Hassen, 2020).[13] In the case of improved cookstoves and other new technologies, the key unanticipated impact that has received significant attention is what is known in the energy economics literature as the "rebound effect". In simple terms, "rebound effect" is used to describe a paradox in fuel-saving technologies acquired by households: adoption of the efficient technology does not lead to reduction in energy use.[14] There is large evidence on the rebound effect from energy-efficient technologies in high-income countries, but there is not much evidence from developing countries. In this subsection, we review studies on the impact of improved (and modern) cookstoves in developing countries, with a significant focus on reduction in fuel use, deforestation, and possible reduction in emission of CO_2.

One of the first studies on the impact of improved cookstoves on households using a randomized controlled trial was conducted by Smith-Sivertsen et al. (2009) in

Guatemala. The key motivation of the study is the vast respiratory problem of women in developing countries, who often burn biomass fuel to cook for their households. The authors randomly offered ICS known in the area as "plancha" to women in the highlands of Guatemala aged 15-50 years. They measure the impact of the stoves on indoor air pollution and related health symptoms and assess chronic respiratory symptoms, lung function, and individual carbon monoxide exposure at baseline and every six months up to 18 months. Smith-Sivertsen et al. (2009) show that, the use of a plancha reduced carbon monoxide exposure by 61.6%. They also document that plancha users reported reduction in the number of respiratory symptoms at each follow-up. However, they do not find statistically significant effects on lung function after 12-18 months. The authors concluded that ICS reduce indoor air pollution, and, consequently, relieve symptoms of chronic respiratory irritation.

Probably one of the first ICS randomized controlled trials designed to measure the impact of ICS on households' fuel use, exposure to smoke, and reported health, was conducted by Burwen and Levine (2012) in Ghana. The authors recruited 768 participants from eight villages in the upper west region of Ghana, where the three-stone traditional stove is the common cooking technology. The treatment group (about half of the sample) was trained on how to build and properly operate an ICS that saves fuel and releases smoke in a chimney using local materials. The authors did not find a statistically significant reduction in fuel use eight weeks after the stoves have been built. Neither did they find detectable reductions in households' weekly wood gathering time or exposure to carbon monoxide. However, they document a significant decline in participants' reported symptoms associated with cooking, such as burning eyes and respiratory symptoms. Using electronic stove monitors attached to the stoves, the authors find that treatment households used their ICS on about half of the days monitored and reduced the use of their traditional stoves by about 25%. Burwen and Levine (2012) conclude that the ICS were not successful in achieving their intended objective. The key reason is likely because the ICS did not meet the cooking needs of households, although they were designed to reduce fuel use. The experiment demonstrated that, for ICS initiatives to be successful the designs should meet the cooking needs of households, and policies that discourage the use of the traditional stoves should be in place.

Improved cookstove studies attempting to measure the impact on fuel consumption in Latin America are very scarce. Although the proportion of households with access to modern cooking fuels, such as electricity and gas, is larger than in Africa and South Asia, there is still large-scale consumption of wood for cooking and heating in the region.[15] Adrianzén (2013) uses an instrumental variables estimation method to identify the impact of ICS on fuelwood consumption distributed in the Chalaco District in the Northern Peruvian Andes. Some of the ICS distributed had faulty metal frames, which made them break down shortly after use. The author uses the faulty frames (which were argued to be random) as instruments for stove use, and estimates the impact on fuelwood consumption. Adrianzén (2013) shows that improved cookstoves reduced fuelwood consumption by about 46% during a typical wet month, which translates to about 650kg of firewood per user household for the entire wet season. Such reduction in firewood use has significant effects, both on households (through reduced time fetching firewood) and the environment (through reducing the pressure on forest resources).

Bensch and Peters (2015) and Gebreegziabher et al. (2018) also investigate the impact of ICS on fuel consumption and reported health of household members in an African setup using large scale randomized controlled trials. Bensch and Peters (2015) distributed ICS, known in Senegal as the “Janbaar”, which cost US$10, free of charge to 250 households in 12 rural villages. The Janbaar stove has been shown to be portable, with a fired clay combustion centre enclosed by a metal casing. Its design allows firewood to burn more efficiently, by conserving and directing the heat towards the cooking pot. The treatment group received the Janbaar stove. The control group received a 5kg bag of rice for participating in the survey. Bensch and Peters (2015) measure the impact of the stove 12 months after stove distribution. They show that households in the treatment group reduced firewood consumption by 30% compared to the control group. But they argue that these effects are lower than the ones documented in controlled cooking tests, the key reasons being households likely kept on using the traditional stove together with the new stove. Treatment households also reported a 50% decline in respiratory symptoms and a 20% decline in cooking time by women. Bensch and Peters (2015) provide credible evidence that durable ICS designed to meet the cooking needs of households would likely be adopted and used by households frequently, resulting in the promised positive impacts on households and the environment.

Gebreegziabher et al. (2018) provide more insights from rural Ethiopia on the magnitude of the impact of an ICS on fuelwood use and cooking time. The authors distributed the “Mirt” stove similar to the one used by Alem et al. (2018), an improved firewood stove used to bake the local staple called “Injera”, to households in 36 villages and three regions (Amhara, Oromia, and Southern Nations, Nationalities and Peoples). They conducted a controlled cooking test for both the Mirt stove and the traditional three-stone stove (the widely used cooking technology in the study villages) in two sessions separated by 5-6 months. Gebreegziabher et al. (2018) find that, compared to the traditional stove, the Mirt stove reduced fuelwood consumption per kilogram of injera by 22%-31%. The reduction in fuelwood is less than the reduction laboratory test results suggest, which is 50%. Their results also suggest that fuelwood saving increases over time, which very likely is attributed to learning how to use the new stove. In a companion study which draws on the same field experiment, Beyene et al. (2015) use electronic stove monitors and show that households kept on using the new stove more frequently, and involving community-level user networks led to more use. Despite the popular belief that households use products more when they pay for them, the authors find that offering the stoves for free resulted in more use.

Understanding the complete and sustained impact of improved cookstoves requires, not only distributing the stoves following standard impact evaluation designs, but also collecting follow-up data a long time after the stoves have been distributed. Such a study was conducted by Hanna et al. (2016). In collaboration with a local NGO, these authors distributed improved chimney stoves (valued at US$12.5) to 2,600 households in 44 villages in the Orissa state of India. Then, they evaluated the impact of the stoves on indoor air pollution, health of household members, and emission of greenhouse gases over four years after the stoves had been distributed. The NGO distributed the stoves to a third of households in the first year using public lotteries. The second third of households received the stoves after two years. The remaining households received the stoves at the end of the fourth year.

Hanna et al. (2016) find that initial take-up and usage of the ICS was low and declined over time, which clearly means that households kept on using their old stoves as well. The authors document a significant reduction in smoke inhalation in the first year, but there was no effect after the first year. There was no difference in objectively measured health outcomes (lung functioning) and reported health (infant birth weight, infant mortality rates and coughing, etc.) between the treatment and control group. There was also no reduction in wood used for cooking and emission of greenhouse gases. Overall, the stoves did not result in the fuel and smoke reduction observed in laboratory settings. The authors argue that the key reasons for such disappointing results are stove breakage, lack of sufficient maintenance services, and inappropriate cleaning and use. In fact, the stoves appeared to have negative effects on treatment households, because they had to spend more time repairing them. Hanna et al. (2016) argue that the key lessons learned from their evaluation are that, to succeed in adoption by households and produce the anticipated positive impacts, improved cookstoves must be affordable, easy to transport to remote areas, and easy to clean and maintain.

One important aspect of modern technologies in general, and improved cookstoves in particular, is the introduction of other positive benefits beyond the intended purpose, which very often include saving fuelwood and reducing indoor air pollution and fuelwood collection time. In a recent comprehensive study, Alem and Hassen (2020) investigate the impact of the Mirt improved cookstove on time allocation and off-farm employment opportunities of women in Northern Ethiopia. They distributed the stove to half of the 300 households (the treatment group) living in six villages and offered a bag of wheat (25kg) with comparable value to the control group. They measured the impact of the stove on several outcome variables 16 months after the stoves had been distributed. Consistent with what has been documented by Gebreegziabher et al. (2018), Alem and Hassen (2020) find that the stove indeed reduced firewood consumption by 35% in the treatment group 16 months after distribution. Due to the efficiency gain from using the improved stove, households in the treatment group reallocated animal dung and crop residue from cooking to their farms, which likely improves land productivity. They also find that women in the treatment group reduced their cooking and fuel collection time by 20% and 41%, respectively, and their likelihood of allocating time to poultry and livestock keeping increased by 27.6%. Thus, in addition to reducing fuel consumption, indoor air pollution and cooking time, improved cookstoves clearly offered increased income for women and households. The study provides important insights on the extended impacts of introducing well-designed improved cookstoves in poor communities.

Previous studies that involved distribution of stoves in an experimental setup almost exclusively focus on rural areas and improved biomass cookstoves. Although under-investigated, the environmental impact of biomass fuel consumption by urban households is substantial. In fact, production of charcoal to meet cooking needs of urban (and mostly middle-income) households has been one of the key causes of deforestation and degradation of forests in Africa (Campbell et al., 2007; World Bank, 2009, 2014; Mercer et al., 2012). Consistent with the "energy ladder" and "energy stacking", theories, which have been widely used to describe energy use behaviour of households in developing countries (Barnes et al., 2005; Heltberg, 2005; Leach, 1992; Masera et al., 2000),[16] the proportion of households using charcoal as their primary cooking energy is expected to rise significantly in the coming decades in sub-Saharan Africa. In urban Tanzania, for example, World Bank (2009) shows that the proportion of households that use charcoal as their main cooking energy source increased from 47% in 2001 to 71% in 2007. Dar es Salaam city alone consumes 500,000 tonnes of charcoal, half of the total annual charcoal consumption of the country. Charcoal production, which is conducted almost exclusively using traditional and inefficient methods, with a conversion efficiency of 8-12%, costs Tanzania 125,000ha of forest and woodland every year (World Bank, 2009).

The only large-scale randomized controlled trial on the impact of modern cooking appliances on the welfare of urban households and the environment (Alem & Ruhinduka, 2020) documents that the two-burner LPG stoves they offered reduced charcoal consumption by 30% 15 months after the stoves had been distributed. This corresponds to reducing deforestation by 0.04ha per household/year, which averts 5.93 metric tonnes (MT) of CO_2 per household/year. Households that acquired LPG stoves through subsidy used the stoves more and reduced charcoal consumption by a larger magnitude (38%) than credit households (27%) 15 months after the interventions. Due to the efficiency of LPG stoves in cooking, treatment households also reduced daily cooking time by 44%. A carefully conducted controlled cooking test reveals that, once a household has acquired an LPG stove, the cost of cooking (the cost of the gas) is 50% lower than the cost of charcoal. The findings clearly show that switching to modern cooking appliances is highly beneficial both to the household and the environment.

Impact on CO_2 emission and cost-benefit analysis

Some of the studies reviewed in this paper show that, if affordable improved biomass and modern cookstoves that meet the expectations of households become available and liquidity constraints are addressed, households will adopt and use them consistently. As a result, they will reduce fuel consumption, deforestation and degradation of forests (and, consequently, emission of harmful greenhouse gases), and improve the welfare of households. Thus, the key public policy question is: what is the value of a successful ICS to society? In this subsection, we draw on two reliable studies that document reduction in fuel use in Africa—Gebreegziabher et al. (2018) in rural Ethiopia and Alem and Ruhinduka (2020) in urban Tanzania—and attempt to shed light on the implications of ICS adoption on deforestation and emission of CO_2. Using the Social Cost of Carbon (SSC), we also conduct a cost-benefit analysis and offer insights for public policies and programmes that promote improved cookstoves.

Gebreegziabher et al. (2018) and Alem and Hassen (2020) document that, households in rural Ethiopia using the traditional cookstove consume 130kg of firewood/month, i.e., 1,560kg/year, but adoption of the Mirt stove reduced firewood consumption by about 35%. The reduction in firewood consumption can easily be translated to reduction in deforestation and averted carbon dioxide (CO_2). The Food and Agricultural Organization (FAO) estimate that, on average, Ethiopian woodlands contain 10-50 cubic metres[17] of wood per hectare. If one takes the absolute minimum amount of wood product that would be harvested, i.e., 10 cubic metres, households using the traditional stove consume 1.56[cubic metres or 0.16ha of woodland/year. Thus, owning an improved Mirt stove reduces forest clearing by 0.55 cubic metres per year. Hansen et al. (2013) show that the average carbon stored per hectare of forest cover in Africa is 153.5 metric tonnes (MT). Thus, one ICS leads to reduction of 0.06ha of woodland deforestation and aversion of around 9.21MT of CO_2 per year. The United States Environmental Protection Agency (US EPA) estimates the SCC of one MT of averted CO_2 to be US$39 in 2012 (Jayachandran et al., 2017). The total SCC value of averted CO_2 sums up to US$359.19 per Mirt stove. Given the market price of the stove is US$10, under full subsidy, the net benefit of the stove would be US$349.19 (i.e., US$359.19 less US$10). These values do not account for other benefits of forests and woodlands, such as the value of biodiversity. It is, therefore, evident that the benefit of subsidizing ICS distribution is massively higher than their cost.

Is supporting distribution of modern and costly cooking appliances, such as LPG stoves, beneficial to society? Alem and Ruhinduka (2020) translate the large reduction in charcoal consumption they document due to adoption of LPG stoves into reduction in deforestation and aversion of CO_2 emission. Accounting for the CO_2 emitted from LPG stoves, the net reduction in charcoal consumption by treatment households is equivalent to 0.04ha of forest and 3.91MT of net CO_2 per household/year; 0.03ha (3.53MT of CO_2) for the credit treatment group; and 0.05ha of forest (5.03MT of CO_2) per household/year for the subsidy treatment group. Table 1 shows the results of the cost-benefit analysis. It clearly reveals that the net benefit that accrues to society by offering LPG stoves through subsidy and credit programmes is US$112.88 and US$95.99 per LPG stove, respectively. Carefully-designed subsidy and micro-finance opportunities that address liquidity constraints of households can therefore offer a double dividend—improve household welfare and conserve the remaining forest resources of Africa.

Table 1: Cost-benefit analysis of LPG subsidy and credit policy - urban Tanzania

	(1)	(2)	(3)
	Subsidy	**Credit**	**All**
Reduction in charcoal consumption per LPG stove (%)	0.38	0.27	0.30
Reduction in deforestation per LPG stove/year in hectares	0.05	0.03	0.04
Gross CO_2 averted in MT (153.5MT per hectare)	7.62	5.35	5.93
CO_2 emitted from cooking with LPG in MT (eq. to 34%)	2.59	1.82	2.02
Net CO_2 averted	5.03	3.53	3.91
Social Cost of Carbon (SCC) in saved forest (US$39/MT of CO_2)	196.21	137.66	152.55
Average cost of programme per unit of LPG in USD	83.33	41.67	62.50
Average cost of programme per MT of CO_2 averted	16.56	11.81	15.98
Average net benefit per LPG	112.88	95.99	90.05

Notes: This table reports social cost-benefit analysis of the subsidy and credit treatments. Column 1 presents reduction in charcoal consumption and deforestation, taking into account the CO_2 averted, including its cost and benefit to society due to subsidizing 75% of the cost of LPG stoves. Columns 2 and 3 report the same information for the credit treatment group and both treatment groups combined, respectively.
Source: Alem and Ruhinduka (2020).

4. Missing links in stove and energy use research

There are a number of issues which future research on energy choice and stove use behaviour in developing countries can address.

First, previous impact evaluation studies that did not find significant effects in reduction of fuelwood and indoor air pollution (Hanna et al., 2016; Burwen & Levine, 2012) are helpful in stressing the importance of the pre-distribution precautions that should be taken by governments, donors and NGOs. ICS should meet the cooking needs of households, and they should be easy to transport, install, clean, and maintain. Stove distributors should also conduct extensive piloting in different environments before large scale distribution. Once this stage is passed, the biggest challenge of convincing households to adopt the stoves remain — affordability. Studies consistently proved that in poor communities, improved stoves priced as low as US$5 are still unaffordable, compared to traditional stoves, which are very often built easily using local materials. There is ongoing debate on whether households should pay for new welfare-enhancing technologies or the technologies should be distributed free of charge (Kremer & Miguel, 2007; Cohen & Dupas, 2010; Tarozzi et al., 2014). Nonetheless, existing studies robustly identify liquidity constraint as the main reason for the low uptake of improved cookstoves. Consequently, making them affordable through subsidy and credit options is crucial. The option of improving households' ability to pay for new technologies through public work opportunities, as was successfully implemented by Alem et al. (2018), is a promising example. Poor households may lack the cash to pay for ICS upfront, but they often have enough labour to pay for it in the form of public work. More research on the effectiveness of different forms of relaxing households' liquidity constraints to improve WTP for improved cookstoves is therefore crucial.

Second, evaluating the impact of ICS on outcome variables, such as fuel consumption, indoor air pollution, and health, requires designing the evaluation programme following standard impact evaluation protocols. This aspect is important as well for other interventions that are distributed to improve the welfare of households. These impacts evaluation design issues range from ensuring the internal and external validity of the experiments to ethical dimensions, in the programme inception, design, implementation, and the write up of the research findings. An important issue that comes up in designing any randomized controlled trial is determination of sample size through statistical power calculation. In simple terms, statistical power is the probability that the researcher will reject the hypothesis of zero effect for a given effect size and a given statistical significance level (α). Design choices (such as the number of treatment arms) and sample sizes will affect the power of an experiment (Duflo et al., 2007). Among the stove studies reviewed in this paper, only Bensch and Peters (2015), Beltramo et al. (2015), Smith-Sivertsen et al. (2009), and Alem and Hassen (2020) determine their sample size using statistical power calculation. For randomized controlled trials to offer reliable treatment effects, the sample size and the number of treatment arms should be determined through standard statistical power analysis.

The third gap that future research can address is the geographical focus of ICS studies. A large proportion of existing stove studies focus on rural households. This is understandable, given that a large proportion of households in low-income countries live in rural areas. Nevertheless, urban households consume a large amount of biomass fuel, most importantly charcoal. Studies (Campbell et al., 2007; World Bank, 2009, 2014; Mercer et al., 2012) have already confirmed that the large-scale unsustainable production of charcoal to meet cooking needs of urban households is one of the key drivers of deforestation and forest degradation. Households in urban areas have better access to modern (and clean) energy sources, but the limited research (Alem & Ruhinduka, 2020) has already shown that they don't have the financial ability to pay for the cost of modern cooking appliances. More research is needed on the effectiveness of different micro-finance and repayment schemes to encourage households to switch to modern energy sources and reduce biomass fuel consumption. Moreover, studies from the developing region of Latin America are scarce. More research is needed on biomass fuel use and its impact in the region.

Fourth, improved cookstoves are distributed with the aim of reducing biomass fuel consumption and indoor air pollution, improving the health of household members, and reducing the time cost of fuelwood collection and cooking. But an important question is: what do women (who by default are responsible for cooking and collecting fuelwood) do with the time they save due to having access to an ICS? The study by Alem and Hassen (2020) is the only impact evaluation study that attempted to provide insight on this question. Women in Northern Ethiopia used the time they saved from cooking and fuelwood collection to engage in livestock and poultry keeping. Because of the reduction in fuel used for cooking after owning an ICS, households relocated manure and animal dung to farms. These findings suggest that, if ICS provide benefits to households beyond fuel saving and reduction in indoor air pollution, the social value of the stoves would be substantially higher than what existing studies document. Moreover, new technologies, such as ICS, are likely to have other general equilibrium effects in remote villages. Their introduction creates a market and supply chain for production, distribution, and maintenance (Pattanayak et al., 2019), which implies that they create jobs, new skills, and other complementary production activities. Future research which addresses these issues will play a significant role in improving our understanding of the economics of improved cookstoves.

Finally, all existing experimental studies on cookstoves reviewed in this paper exclusively focus on households. Analysing energy use behaviour of small and medium-scale enterprises, such as restaurants, pubs, and food processing enterprises, is important because the amount of biomass fuel consumed by the sector is substantial. According to UNECA (2011), around 8550% of the primary energy supply in SSA comes from biomass sources, and the industrial sector consumes 40% of it. Consequently, promoting energy transition of households to modern sources, while ignoring biomass energy use by firms, is likely to result in significant economy-wide leakages, as more biomass fuel will be available and consumed by firms. As a result, there is an urgent need to study the energy use behaviour of micro, small and medium-scale enterprises, and the possible policy options to help them shift to clean energy sources, including the corresponding implications on productivity and resource allocation.

5. Conclusions

This paper has reviewed existing studies which investigate the factors that promote adoption of improved cookstoves (ICS) in developing countries and their impact on household outcomes, with a particular focus on biomass fuel consumption and the environment. While the insights generated from studies using observational data and statistical methods are useful, they do not enable policy makers to understand the causal effects of distributing improved cookstoves. Consequently, the paper focused on studies that were conducted using rigorous impact evaluation designs and statistical methods.

Review results suggest that the key driver of uptake of appropriately designed ICS is liquidity constraints. Households in poor communities lack the financial resources to pay the upfront cost of ICS. A social cost-benefit analysis that considers the costs and the benefits of ICS to society suggests that subsidizing ICS offers substantial benefits to society at large. Because forest resources sequester carbon, they often have a global good nature. Channelling resources to support ICS dissemination is cost-effective. Results also robustly show that empowering and engaging women, who are responsible for cooking and fuelwood collection, but who lack the decision-making autonomy to make purchase decisions, is crucial for uptake of ICS. Once adoption constraints are addressed, for households to consistently use the ICS, the stoves should meet their cooking needs, and they should be easy to transport, install, clean, and maintain. If these conditions are met, households use ICS and reduce their biomass fuel use, and this consequently reduces the pressure on biomass resources.

This review generates five important knowledge gaps that future research may address. First, given the importance of liquidity constraint, and the debate on whether ICS should be offered to households free of charge, more research is needed on the effectiveness of different mechanisms, such as stove-for-work programmes and micro-finance services. Second, in order to improve reliability of estimates of the impact of ICS, studies should be guided by proper impact evaluation protocols, such as determining sample size using statistical power analysis. Third, much of the literature on the impact of ICS focuses on fuelwood consumption, indoor air pollution, and health. More research is needed on the effects beyond fuel and time saving, such as time allocation of women. Fourth, urban households are under-represented in stove studies, but more studies on urban households are needed, because they consume a substantial amount of biomass fuel, most notably charcoal. Finally, and most importantly, all existing stove studies focus on households. Micro, small and medium-scale enterprises in Africa consume nearly half of the biomass fuel consumed in the continent. Experimental work on firm energy use behaviour and transition to cleaner sources is urgently needed to complete our knowledge of biomass energy use behaviour and its full implications in developing countries.

Notes

1. According to Mercer et al. (2012), 30 million hectares of Africa's forest was deforested during 2000- 2010, and 80% of the harvested wood was burned to meet cooking energy needs.

2. Although it is the second major greenhouse gas, methane has been proven to have 25 times higher potential of trapping heat in the atmosphere than CO_2 (vanDam, 2017; USEPA, 2012).

3. Ritchie and Roser (2019) show that, indoor air pollution is responsible for 6% of all deaths in SSA and South Asia, but it is responsible for only 0.1% of deaths in Europe and North America.

4. Out of the 18 studies reviewed, 11 were conducted in Africa, five in South Asia, and two in Latin America.

5. See, Barnes et al. (1993); Lewis and Pattanayak (2012); Malla and Timilsina (2014) for review of improved cookstove and fuel choice studies in developing countries using observational data. See also Jeuland et al. (2021) for a recent comprehensive systematic review of the social science literature on the quantified impacts of energy on society in the context of developing countries.

6. We used online databases to search for relevant articles that have been published in both peer- reviewed journals and working paper series using the impact evaluation methods discussed in this section.

7. The other commonly used quasi-experimental impact evaluation method, which has been extensively used in the impact evaluation literature, is the Propensity Score Matching (PSM) method of Rosenbaum and Rubin (1983). This estimator is based on the assumption of conditional independence, which implies that programme participants select themselves in a programme based on their observable characteristics only. This assumption has been shown not to hold in many instances, because programme participants self-select into programmes based on unobservable characteristics as well. Consequently, the use of the estimator in impact evaluation has been limited in recent years. PSM can however yield consistent programme effect estimates if used in combination with the DID. See Khandker et al., (2010) for details.

8. See, Barnes et al. (1993) for details.

9. In many low-income communities, children also benefit from reduced fuelwood collection time and reduced indoor air pollution (World Bank, 2011).

10. See, http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm for a description of the "Mirt" stove.

11. The authors measured autonomy of wives and autocracy of husbands using survey questions about who makes decisions regarding purchase of the wife's personal items (e.g., clothes and shoes).

12. The market price of the two-burner LPG stove, US$110, is comparable to five months consumption expenditure of the average urban Tanzanian. To put things in perspective, a two-burner LPG stove costs 15 times the average price of the improved cookstoves studied in this review.

13. There is documented evidence on the unanticipated negative effects of new technologies in developing countries. For example, mosquito bed nets distributed to protect household members from malaria were widely used for over-fishing in Africa (McLean et al., 2014; Jones & Unsworth, 2020).

14. See, IRGC (2013) for a survey of the literature and the different aspects of the "rebound effect" of energy technologies.

15. The proportion of households with access to clean fuels for cooking as of 2016 is 45.2% in Guatemala, 53.1% in Honduras, 52.3% in Nicaragua, 64% in Bolivia, and 75.6% in Peru. Source: https://ourworldindata.org/energy.access

16. The "ladder" theory postulates that households consume biomass fuels such as fuelwood and charcoal at lower levels of income and switch to modern fuels such as kerosene, natural gas, and electricity as their income increases. The "stacking" theory, on the other hand, hypothesizes that households continue to use multiple traditional fuels together with modern fuels for various reasons (Barnes et al., 2005; Heltberg, 2005; Leach, 1992; Masera et al., 2000).

17. See, http://www.fao.org/3/ab582e/AB582E02.htm

References

Adrianzén, M.A. 2013. "Improved cooking stoves and firewood consumption: Quasi-experimental evidence from the northern Peruvian Andes". *Ecological Economics,* 89: 135–43.

Alem, Y. and E. Demeke. 2020. "The persistence of energy poverty: A dynamic probit analysis". *Energy Economics*, 90: 1–11.

Alem, Y. and E. Dugoua. 2021. "Learning from unincentivized and incentivized communication: A randomized controlled trial in India". *Economic Development and Cultural Change*. Forthcoming.

Alem, Y. and R. Ruhinduka. 2020. "Saving Africa's tropical forests through energy transition: A randomized controlled trial in Tanzania". RUHR Economic Paper No. 885.

Alem, Y. and S. Hassen. 2020. *The Impact of Improved Cookstoves Beyond Fuel Saving: A Randomized Controlled Trial from Ethiopia*. Unpublished.

Alem, Y., S. Hassen and G. Köhlin. 2014. "Adoption and disadoption of electric cookstoves in urban Ethiopia: Evidence from panel data". *Resource and Energy Economics*, 38: 110–24.

Alem, Y., S. Hassen and G. Köhlin. 2018. "Decision-making within the household: The role of differences in preference and autonomy". Working Paper No. 19-17. Department of Economics, University of Gothenburg.

Allen, J.C. and D.F. Barnes. 1985. "The causes of deforestation in developing countries". *Annals of the Association of American Geographers*, 75(2): 163–84.

Bandiera, O. and I. Rasul. 2006. "Social networks and technology adoption in northern Mozambique". *The Economic Journal*, 116(514): 869–902.

Bardhan, P. and C. Udry. 1999. *Development Microeconomics*. New York: Oxford University Press.

Barnes, D.F., K. Krutilla and W.F. Hyde. 2005. *The Urban Household Energy Transition: Social and Environmental Impacts in the Developing World.* Washington, D.C.: Resources for the Future.

Barnes, D.F., K. Openshaw, K.R. Smith and R. van der Plas. 1993. "The design and diffusion of improved cooking stoves". *The World Bank Research Observer*, 8(2): 119–41.

Becker, G.M., M.H. DeGroot and J. Marschak. 1964. "Measuring utility by a single-response sequential method". *Behavioral Science*, 9(3): 226–32.

Beltramo, T., G. Blalock, D.I. Levine and A.M. Simons. 2015. "The effect of marketing messages and payment over time on willingness to pay for fuel-efficient cookstoves". *Journal of Economic Behavior and Organization*, 118: 333–45.

Bensch, G. and J. Peters. 2015. "The intensive margin of technology adoption - Experimental evidence on improved cooking stoves in rural Senegal". *Journal of Health Economics,* 42: 44–63.

Bensch, G. and J. Peters. 2020. "One-off subsidies and long-run adoption - Experimental evidence on improved cookstoves in Senegal". *American Journal of Agricultural Economics*, 102(1): 72–90.

BenYishay, A. and A.M. Mobarak. 2019. "Social learning and incentives for experimentation and communication". *The Review of Economic Studies,* 86(3): 976–1009.

Berkouwer, S.B. and J.T. Dean. 2020. Credit and Attention in the Adoption of Profitable Energy Efficient Technologies in Kenya.

Beyene, A.D., R. Bluffstone, Z. Gebreegziabher, P. Martinsson, A. Mekonnen and F. Vieider. 2015. "Improved biomass stove saves wood, but how often do people use it? Evidence from a randomized treatment trial in Ethiopia". Policy Research Working Paper No. 7297. Washington, D.C., The World Bank Group.

Burwen, J. and D.I. Levine. 2012. "A rapid assessment randomized-controlled trial of improved cookstoves in rural Ghana". *Energy for Sustainable Development*, 16: 328–38.

Campbell, B., A. Angelsen, A. Cunningham, Y. Katerere, A. Sitoe and S. Wunder. 2007. *Miombo Woodlands, Opportunities and Barriers to Sustainable Forest Management.* Centre for International Forestry Research (CIFOR).

Cohen, J. and P. Dupas. 2010. "Free distribution or cost-sharing? Evidence from a randomized malaria prevention experiment". *Quarterly Journal of Economics*, 125(1): 1–45.

Conley, T.G. and R. Udry. 2010. "Learning about a new technology: Pineapple in Ghana". *American Economic Review*, 100(1): 35–69.

Duflo, E., R. Glennerster and M. Kremer. 2007. "Using randomization in development economics research: A toolkit". *Handbook of Development Economics*, 4: 3895–3962.

Edwards, J.H.Y. and C. Langpap. 2005. "Startup costs and the decision to switch from firewood to gas fuel". *Land Economics*, 81(4): 570–86.

Feder, G., R.E. Just and D. Zilberman. 1985. "Adoption of agricultural innovations in developing countries: A survey". *Economic Development and Cultural Change*, 33(2): 255-298.

Foster, A.D. and M.R. Rosenzweig. 1995. "Learning by doing and learning from others: Human capital and technical changes in agriculture". *Journal of Political Economy*, 103(6): 1176–1209.

Gebreegziabher, Z., A.D. Beyene, R. Bluffstone, P. Martinsson, A. Mekonnen and M.A. Toman. 2018. "Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia". *Resource and Energy Economics*, 52: 173–85.

Geist, H.J. and E.F. Lambin. 2002. "Proximate causes and underlying driving forces of tropical deforestation". *BioScience*, 52(2): 143–50.

Grieshop, A.P., J.D. Marshall and M. Kandlikar. 2011. "Health and climate benefits of cookstove replacement options". *Energy Policy*, 39: 7530–42.

Hanna, R., E. Duflo and M. Greenstone. 2016. "Up in smoke: The influence of household behavior on the long-run impact of improved cookstoves". *American Economic Journal: Economic Policy,* 8(1): 80–114.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, D. Thau, S.V. Stehman, S.J. Goetz, T.R. Loveland, A. Kommareddy, A. Egorov, L. Chini, C.O. Justice and J.R.G. Townshend. 2013. "High-resolution global maps of 21st-century forest cover change". *Science*, 342(6160): 850– 53.

Heltberg, R. 2005. "Factors determining household fuel choice in Guatemala". *Environment and Development Economics,* 10: 337–61.

Hoffman, V. 2009. "Intrahousehold allocation of free and purchased mosquito nets". *American Economic Review*, 99(2): 236–41.

Hofstad, O., G. Köhlin and J. Namaalwa. 2009. "How can emissions from woodfuel be reduced?" *Realising REDD+: National Strategy and Policy Options*, pp. 237–48.

Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change: Impacts, Adaptation and Vulnerability.* Report, the Intergovernmental Panel on Climate Change.

IRGC, I. R. G. C. 2013. *The Rebound Effect: Implications of Consumer Behaviour for Robust Energy Policies.* Report, International Risk Governance Council.

Jain, T. and M. Kapoor. 2015. "The impact of study groups and roommates on academic performance". *The Review of Economics and Statistics*, 97(1): 44–54.

Jayachandran, S., J. de Laat, E.F. Lambin, C.Y. Stanton, R. Audy and N.E. Thomas. 2017. "Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation". *Science*, 357: 267–73.

Jeuland, M., R. Fetter, Y. Li, S. Pattanayak, F. Usmani, R.A. Bluffstone, C. Chavez, H. Girardeau, S. Hassen, P. Jagger, M.M. Jaime, M. Karumba, G. Köhlin, L. Lenz, E.L. Litzow, L. Masatsugu, M.A. Naranjo, J. Peters, P. Qin, R.D. Ruhinduka, M. Serrano-Medrano, M. Sievert, E.O. Sills and M. Toman. 2021. "Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries". *Renewable and Sustainable Energy Reviews,* 135(110406): 1–22.

Jones, B.L. and R.K.F. Unsworth. 2020. "The perverse fisheries consequences of mosquito net malaria prophylaxis in East Africa". *Ambio*, 49: 1257–67.

Kandlikar, M., C.C. Reynolds and A.P. Grieshopdy. 2009. "A perspective paper on black carbon mitigation as a response to climate change". Copenhagen Consensus on Climate.

Khandker, S.R., G.B. Koolwal and H.A. Samad. 2010. *Handbook on Impact Evaluation: Quantitative Methods and Practices.* Washington, D.C.: The World Bank.

Köhlin, G., E.O. Sills, S. Pattanayak and C. Wilfong. 2011. "Energy, gender and development? What are the linkages? Where is the evidence?" *Policy Research Working Paper*, No.5800.

Közegi, B. and M. Rabin. 2006. "A model of reference-dependent preferences". *The Quarterly Journal of Economics,* 121(4): 1133–65.

Kremer, M. and E. Miguel. 2007. "The illusion of sustainability". *Quarterly Journal of Economics,* 122(3): 1007–65.

Leach, G. 1992. "The energy transition". *Energy Policy*, 20(2): 116–23.

Levine, D.I., T. Beltramo, G. Blalock, C. Cotterman and A.M. Simons. 2018. "What impedes efficient adoption of products? Evidence from randomized sales offers for fuel-efficient cookstoves in Uganda". *Journal of the European Economic Association*, 0(0): 1–31.

Lewis, J.J. and S.K. Pattanayak. 2012. "Who adopts improved fuels and cookstoves? A systematic review". *Environmental Health Perspectives,* 120(5): 637–45.

Lusk, J.L., J.A. Fox, T.C. Schroeder, J. Mintert and M. Koohmaraie. 2001. "Instore valuation of steak tenderness". *American Journal of Agricultural Economics*, 83(3): 539–50.

Malla, S. and G.R. Timilsina. 2014. "Household cooking fuel choice and adoption of improved cookstoves in developing countries: A review". Policy Research Working Paper No. 6903. Washington, D.C., The World Bank.

Masera, O.R., B.D. Saatkamp and D.M. Kammen. 2000. "From linear fuel switching to multiple cooking strategies: A critique and alternative to the energy ladder model". *World Development*, 28(12): 2083–2103.

McLean, K.A., A. Byanaku, A. Kubikonse, V. Tshowe, S. Katensi and A.G. Lehman. 2014. "Fishing with bed nets on Lake Tanganyika: A randomized survey". *Malaria Journal*, 13(395): 1–5.

Mercer, B., J. Finighan, T. Sembres and J. Schaefer. 2012. "Protecting and restoring forest carbon in tropical Africa: A guide for donors and funders". Electronic.

Miller, G. and A.M. Mobarak. 2013. "Gender difference in preference, intra-household externality and low demand for a new technology: Experimental evidence on improved cookstoves". *NBER Working Paper Series*, (18964): 1–34.

Miller, G. and A.M. Mobarak. 2014. "Learning about new technologies through social networks: Experimental evidence on nontraditional stoves in Bangladesh". *Marketing Science*, 34(4): 480–99.

Mobarak, A.M., P. Dwivedib, R. Bailisb, L. Hildemannc and G. Miller. 2012. "Low demand for nontraditional cookstove technologies". *Proceedings of the National Academy of Sciences,* 109(27): 10815–20.

Modi, V., S. McDade, D. Lallement and J. Saghir. 2005. *Energy Services for the Millennium Development Goals.* Technical Report, Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project, and The World Bank.

Oster, E. and R. Thornton. 2012. "Determinants of technology adoption: Peer effects in menstrual cup take-up". *Journal of the European Economic Association,* 10(6): 1263–93.

Pattanayak, S.K., M. Jeuland, J.J. Lewis, F. Usmani, N. Brooks, V. Bhojvaid, A. Kar, L. Lipinski, L. Morrison, O. Patange, N. Ramanathan, I.H. Rehman, R. Thadani, M. Vora and V. Ramanatha. 2019. "Experimental evidence on promotion of electric and improved biomass cookstoves". *Proceedings of the National Academy of Sciences,* 116(27): 13282–87.

Ritchie, H. and M. Roser. 2019. *Indoor Air Pollution.* Technical Report, Our World in Data.

Rosenbaum, P.R. and D.B. Rubin. 1983. "The central role of the propensity score in observational studies for causal effects". *Biometrika*, 70(1): 41–55.

Sagar, A.D. and S. Kartha. 2007. "Bioenergy and sustainable development?" *Annual Review of Environment and Resources,* 32(1): 131–67.

Serdeczny, O., S. Adams, F. Baarsch, D. Coumou, A. Robinson, W. Hare, M. Schaeffer, M. Perrette and J. Reinhardt. 2017. "Climate change impacts in sub-Saharan Africa: From physical changes to their social repercussions". *Regional Environmental Change*, 17: 1585–1600.

Smith-Sivertsen, T., E. Díaz, D. Pope, R.T. Lie, A. Díaz, P. Bakke, J. McCracken, B. Arana, K.R. Smith and N. Bruce. 2009. "Effect of reducing indoor air pollution on women's respiratory symptoms and lung function: The RESPIRE randomized trial, Guatemala". *American Journal of Epidemiology,* 170(2): 211–20.

Sovacool, B.K. 2012. "The political economy of energy poverty: A review of key challenges". *Energy for Sustainable Development,* 16(3): 272–82.

Tarozzi, A., A. Mahajan, B. Blackburn, D. Kopf, L. Krishnan and J. Yoong. 2014. "Micro-loans, insecticide-treated bednets, and malaria: Evidence from a randomized controlled trial in Orissa, India". *American Economic Review*, 104(7): 1909–41.

United Nations Economic Commission for Africa (UNECA). 2011. Fossil Fuels in African in the Context of Constrained Future. African Climate Policy Centre Working Paper No. 12.

United States Environmental Protection Agency (USEPA). 2012. *Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990–2030.* Technical Report, Washington, D.C., United States Environmental Protection Agency.

vanDam, J. 2017. *The Charcoal Transition: Greening the Charcoal Value Chain to Mitigate Climate Change and Improve Local Livelihoods.* Rome: Food and Agriculture Organization.

Verbeek, M. 2017. *A Guide to Modern Econometrics.* John Wiley Sons Inc., 5th Edition. United Kingdom.

World Health Organization (WHO) 2018. *Household Air Pollution and Health.* Technical Report. Geneva, Switzerland: The World Health Organization.

World Bank. 2009. "Environmental crisis or sustainable development opportunity? Transforming the charcoal sector in Tanzania". A Policy Note. Washington D.C., The World Bank Group.

World Bank. 2011. *Household Cookstoves, Environment, Health, and Climate Change: A New Look at an Old Problem.* Washington, D.C.: International Bank for Reconstruction and Development.

World Bank. 2014. "Clean and improved cooking in sub-Saharan Africa". A Policy Note. Washington, D.C., The World Bank Group.

Mission

To strengthen local capacity for conducting independent, rigorous inquiry into the problems facing the management of economies in sub-Saharan Africa.

The mission rests on two basic premises: that development is more likely to occur where there is sustained sound management of the economy, and that such management is more likely to happen where there is an active, well-informed group of locally based professional economists to conduct policy-relevant research.

www.aercafrica.org

Learn More

www.facebook.com/aercafrica

twitter.com/aercafrica

www.instagram.com/aercafrica_official/

www.linkedin.com/school/aercafrica/

Contact Us
African Economic Research Consortium
Consortium pour la Recherche Economique en Afrique
Middle East Bank Towers,
3rd Floor, Jakaya Kikwete Road
Nairobi 00200, Kenya
Tel: +254 (0) 20 273 4150
communications@aercafrica.org