Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management

Philosophiae Doctor (PhD)
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Effects of access to renewable energy sources and technologies on rural household energy use and the environment in Ethiopia

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Yibeltal Tebikew Wassie

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“I sought the LORD, and He heard me, and delivered me from all my fears.” Psalm 34:4

Yibeltal Tebikew Wassie

Ås, November 2020

List of acronyms

ANOVA	Analysis of Variance
BC	Black Carbon
BCR	Benefit -Cost Ratio
CBA	Cost-Benefit Analysis
CO_2e	Carbon dioxide Equivalent
CRGE	Climate Resilient Green Economy
CSA	Central Statistical Agency of Ethiopia
DMR	Direct Matrix Ranking
ETB	Ethiopian Birr (Ethiopian Currency)
FDRE	Federal Democratic Republic of Ethiopia
GHGs	Greenhouse gases
GIZ	German Development Agency
GTP	Growth and Transformation Plan
ICSs	Improved biomass cookstoves
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
Kebele	A cluster of villages (neighbourhoods), the smallest administrative unit of Ethiopia
Kg	Kilogram
L	Litre
m.a.s.l.	Meter above sea level
MJ	Megajoules
MoWIE	Ministry of Water, Irrigation and Electricity of Ethiopia
Mt	Million tone
MTOE	Million ton of oil equivalent
NPV	Net Present Value
PicoPV	A small Photovoltaic system with a power output of up to 10Wp, mainly used for lighting and charging mobile phones
PVs	Photovoltaic systems
RES & Ts	Renewable energy sources and technologies
SDGs	Sustainable Development Goals
SHS	Solar Home Systems
SNNPRS	Southern Nations Nationalities and Peoples Regional State
SNV	Netherlands Development Organization
SRETs	Small-scale renewable energy technologies
SSA	Sub-Saharan Africa (SSA)
Woreda	District (cluster of kebeles), the third-level administrative divisions of Ethiopia after Regional state and Zone
Wp	Watt peak, the maximum electric power output of a solar panel under full solar radiation in Standard Test Conditions

Table of contents

Summary

Access to modern, affordable, and reliable energy and clean cooking facilities is critical for Ethiopia to drive its economic development, reduce poverty and curb the negative environmental and health impacts of traditional and unsustainable use of solid biomass fuels. To that end, the government of Ethiopia has devoted considerable efforts in recent years to improving rural access to electricity, and the dissemination of household biogas systems, solar photovoltaic (PV) systems and improved biomass cookstoves (ICSs). In light of these efforts, the present thesis aims to investigate and empirically examine the effects of access to modern and renewable energy sources and technologies on the rural households' energy use patterns, well-being, and the environment in southern Ethiopia. In doing so, the thesis seeks to shed new light on the nexus between renewable energy access and household energy transition in rural sub-Saharan Africa in the face of climate change. The research was carried out mainly in four rural districts of Southern Ethiopia and data were collected from a comprehensive cross-sectional study (survey) of sample households, direct field assessments, and energy consumption measurements.

The first paper systematically reviews and analyses existing empirical evidence on the potential environmental impacts of small-scale renewable energy technologies (SRETs): biogas, ICSs, and solar PVs in East Africa by taking Ethiopia, Kenya, Tanzania and Uganda as case studies. The results showed that SRETs have considerable potential for reducing household consumption of traditional fuels; thereby lessening forest degradation and the subsequent carbon dioxide (CO_2) emission at local level. Our conservative estimates, based on the evidence, indicated that the biogas plants and ICSs disseminated in each country until 2015, had a combined potential of saving 0.31 to 3.10 million tons (Mt) of woodfuel and reducing emissions of 0.56 to 5.67 Mt of CO_2 equivalent (CO_2e) per country per year. However, when compared with the annual biomass energy consumptions and CO_2 emissions of each country, the biogas and ICSs disseminated till 2015 did not appear to offset more than 7.2% of the total woody biomass energy consumed and 3.8% of the total CO_2e emitted by the respective countries per year.

In light of the evidence from the systematic review in paper I, in paper II we analysed the current utilization rate, performance, and impact of domestic biogas systems in rural southern Ethiopia based on direct field studies and surveys in four districts. The results showed that despite growing efforts, the uptake and utilization of biogas technology is

yet very low. Out of the total 32 digesters directly investigated, only 21 (65.63%) were found functional. The average quantity of biogas produced from a $6m^3$ functional plant was estimated to be 0.61 m^3/day. This suggests that the current level of biogas use could substitute the consumption of 632 kg of fuelwood and 25 L of kerosene per household per year. However, comparative analysis of the total energy consumption of biogas user and non-user households revealed that the effect of biogas use on household fuelwood and kerosene consumptions, and energy transition was insignificant.

Paper III extended the in-depth investigation and examined the potential fuel savings, economic and environmental co-benefits of three ICSs (*Mirt*, *Gonziye,* and *Tikikil* from a survey of 605 sample households and direct kitchen cooking observations to 133 ICSs users. The study finds that compared with the traditional open-fire tripod, the three ICSs studied could reduce household fuelwood consumption on average by 1.72 to 2.08 tons (t)/stove/year. The fuelwood savings translate to an estimated CO_2e emission reduction of 2.82 to 3.43 tCO_2e per stove per year. The results from the cost-benefit analysis (CBA) showed that usage of these ICSs could provide a net economic return of between US$ 317 and $460 during the 2 to 5 years lifespan of the stoves. The study highlighted that beyond improving the energy efficiency and well-being of rural households, ICSs are an essential component of the national and global strategies for GHGs emissions abatement.

In paper IV we explored the impacts of rural electrification with solar PV systems in the study districts based on the survey data and direct field assessment of 137 solar PVs and lanterns. The findings indicated that solar-electrified households consume on average 43.68 litres less kerosene, and emit 107 kg less CO_2 and 2.72 kg less Black Carbon (BC) per year compared with non-electrified households (neither grid nor solar light). This reduction in kerosene consumption and the access to electricity from the solar PVs could enable a solar user household to save between US$ 65 and $75 per year from the avoided energy expenditures and mobile charging costs. The new access to electricity and solar-lighting has also reduced the health risks of rural families from kerosene wick lamps and allowed small-businesses to generate more income. The study concluded that solar PVs and lanterns are improving rural households' wellbeing and access to clean lighting, and therefore should be further integrated into the national energy systems. However, the sustainability and effectiveness of solar PVs faces serious challenges from poor-quality and counterfeit products in the market, high cost of quality-verified products, lack of after-sales maintenance services, and limited access to credit financing services.

In paper V, we analysed the current patterns of rural households' energy consumption and the share of modern and clean fuels to examine the overall effect of access to modern and renewable sources and technologies on rural household energy use and transition. The results showed that more than 97% of the households still rely on traditional solid biomass fuels, particularly fuelwood (90.7%) as the primary fuel for cooking and baking *Injera* (Ethiopian bread). In contrast, the use of biogas and electricity for cooking was limited. On the other side, 50% use kerosene, 29% grid electricity, 19% solar, and 1.98% biogas as primary energy sources for lighting. Of the total 87, 172 MJ energy estimated to be consumed by a rural household per year, energy derived from traditional biomass fuels accounted for 85, 278 MJ (97.83%); while energy from modern and clean sources (electricity, biogas and solar) combined accounted for only 830 MJ (≈ 1%). The findings indicated that the recent efforts of Ethiopia to improving the rural access to modern and renewable energy sources have led to significant lighting energy substitution and partial transition from kerosene oil-based towards clean lighting fuels. However, we found no evidence of substantive energy substitution to suggest that the heavy dependence on traditional solid biomass fuels for cooking and baking end-uses is declining.

Given the findings in paper V, in paper VI, we examined the major determinants of rural household's energy choices for cooking and lighting by using Pearson's Chi-square (χ2) test and Multivariate probit model. The results indicated that rural household's primary cooking fuels are statistically significantly associated with the household size, distance to wood source, location, and income level. Empirical results of the multivariate analysis showed that rural households' energy choices for lighting are significantly influenced by income level, family size, location, educational status, distance to market, road access. We find that wealthier and more educated households residing near road access were more likely to use clean lighting energy such as electricity and solar power; while poorer households residing in areas with limited road access use kerosene and dry-cell battery. However, the results also indicated that high-income level and grid-connection have not led households to completely forgo the use of traditional cooking and lighting fuels. This pattern appears to observe the energy-stacking model as opposed to the energy-ladder model of complete fuel-switching. While income remains a principal factor, the study finds that several non-income factors also play a major role in determining the energy choices and energy transition of rural households in developing countries.

Overall, this PhD thesis provides new empirical evidence and fresh insights to inform decision making and energy planning on the socio-economic, environmental, and energy transition effects of access to renewable energy sources and improved cookstoves; and the associated drivers, challenges, and determinants in the context of rural sub-Saharan Africa. The thesis has shown that increased access and use of modern and renewable energy sources such as electricity and solar in rural areas of developing countries can lead to significant energy substitution and transition from kerosene towards clean and quality lighting. It has also revealed that promoting the use of ICSs is a viable option and an essential component of the strategy for reducing deforestation, mitigation of climate change, and sustainable use of biomass in sub-Saharan Africa. The low rate of utilization and impact from household biogas systems, on the other hand, signifies that thorough re-examining of existing dissemination approaches and operational practices is critical. Most importantly, the thesis has highlighted that the nexus between access to modern and renewable energy; and household energy transition in rural sub-Saharan Africa is complex and non-linear. As such, traditional biomass fuels will likely remain the primary energy sources of even the wealthiest households that are connected to the grid.

The implication is that solid biomass-energy dependent countries like Ethiopia need to critically address the growing demand for biomass fuels through developing sustainable and diversified bio-energy sources, energy-saving and affordable cooking technologies, and decentralized renewable rural hybrid energy systems alongside the current efforts of improving rural access to grid electricity. Although the data for this study is primarily from rural southern Ethiopia, the conclusions and policy implications drawn can have a wider application in the broader context of rural sub-Saharan Africa.

List of papers

This PhD thesis consists of the following six papers that are referred to by their roman numerals in the text (I-VI):

I. Wassie, Y.T., Adaramola, M.S. (2019). Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. *Published in Renewable and Sust. Energy Rev., 111: 377-391.*

II. Wassie, Y.T., Adaramola, M.S. Analysing household biogas utilization and impact in rural Ethiopia: Lessons and policy implications for sub-Saharan Africa.
(Under review in Scientific African)

III. Wassie, Y.T., Adaramola, M.S. Analysis of potential fuel savings, economic and environmental effects of improved biomass cookstoves in rural Ethiopia.
(Under review in Journal of Cleaner Production)

IV. Wassie, Y.T., Adaramola, M.S. Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from southern Ethiopia.
(*Under review in Journal of Energy for Sustainable Development*)

V. Wassie, Y.T., Adaramola, M.S., Rannestad, M. M. Household energy consumption patterns and the share of renewable and modern energy sources in rural southern Ethiopia. (*Under review in Journal of World Development Perspectives*)

VI. Wassie, Y.T., Adaramola, M.S., Rannestad, M. M. Determinants of household energy choices in rural sub-Saharan Africa: An example from southern Ethiopia.
(*Under review in Journal of Energy)*

SYNOPSIS

1. Introduction

1.1. Ethiopia's energy situation and household energy use

The energy balance of most developing countries is dominated by traditional solid fuels particularly traditional solid biomass fuels (fuelwood, crop residues, charcoal and dung-cakes) (Foell et al., 2011; Muller and Yan, 2018). According to IEA's recent estimates, about 890 million people (80% of the population) in sub-Saharan Africa (SSA) depend on traditional solid biomass fuels as their primary energy sources for cooking; and 600 million people (55% of the population) have no access to electricity, and therefore rely heavily on fossil fuels for lighting (IEA, 2018a). This overreliance and unsustainable use of solid biomass fuels in inefficient traditional open-fire cookstoves has been among the major drivers of deforestation, forest degradation and emission of carbon dioxide (CO_2) in the region (Bailis et al., 2015; Mwampamba, 2007; Ndegwa et al., 2016; Obiri et al., 2014). In the mostly un-electrified rural areas of the SSA in particular, lack of access to modern, reliable, and clean energy services**,** and chronic energy poverty remain major impediments to improving the socio-economic development, education, health care, and environmental conditions of the rural poor (Deichmann et al., 2011).

Ethiopia is endowed with diverse renewable energy resources with a total economically feasible estimated power generation potential of 45,000 megawatts (MW) from hydro-power; 7, 000 MW from geothermal; and technically feasible 100, 000 MW from wind power; and abundant solar power with average irradiance of 5.5 kWh/m^2/day, (Lemma, 2014; MoWIE, 2013). If this large energy potential is properly developed and effectively harnessed, Ethiopia could not only achieve energy security to drive and sustain its socio-economic development but could also generate substantial revenue from power exports to regional markets (Khan and Singh, 2017).

Despite this large potential, however, Ethiopia's energy sector, like most other countries in the SSA, relies heavily on traditional biomass energy sources, particularly woodfuels. Aside from the considerable progress made in hydro-power generation in recent years, Ethiopia's energy balance remains biomass-based with inefficient end-use facilities. As shown in Figure 1a, out of the total 51.54 MTOE (million tons of oil equivalent) primary energy supply in 2016, traditional biomass energy accounted for 47.05 (91.40%) while electricity constituted only 0.895 mtoe (1.74%) (IEA, 2018b).

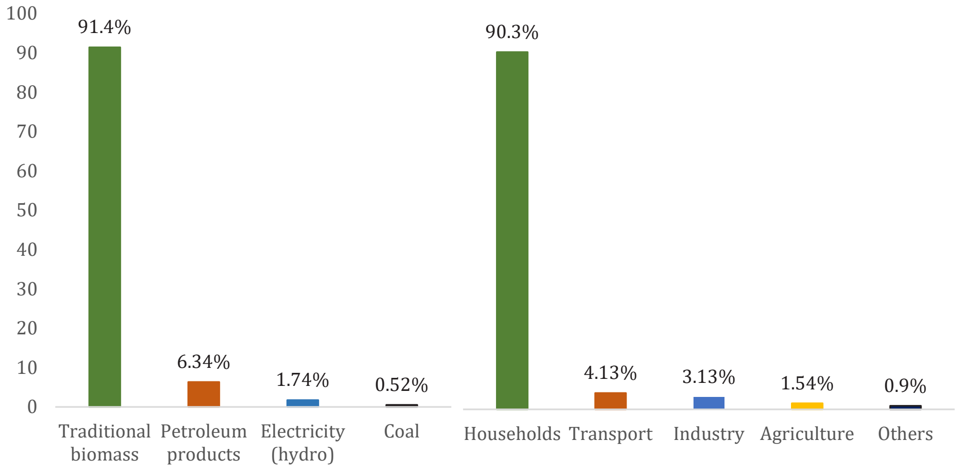

Figure 1a. Share of total primary energy supply by source; and Figure 1b share of final energy consumption by sector in Ethiopia in 2016 (IEA, 2018b)

In the final energy consumption, biomass constituted 37.87 (90%) out of the total 42.15 mtoe of energy consumed in the country in 2016 (IEA, 2018b). A closer look at the share of different sectors in the total final energy consumption (Figure 1b) reveals that the household sector is by far the largest energy consumer accounting for more than 90% of the total energy consumed (IEA, 2018b; Mondal et al., 2018). According to Yurnaidi and Kim (2018), within the Ethiopian household sector, about 98% of the total final energy consumed in the 2014 to 2015 period was derived from primary and delivered biomass energy. And more than 90% of the total energy consumed by the household sector is used for cooking and '[1]Injera' baking (Kebede and Kiflu, 2014; Mulugeta et al., 2017).

In rural areas where 80% of Ethiopia's over 109 million people (as of 2018) live (World Bank, 2018), access to modern energy services is simply unavailable, and traditional use of biomass energy and kerosene dominates the household energy supply. According to Mondal et al. (2018), out of the total final energy consumed by the Ethiopian household sector in 2012, the energy consumed by rural households accounted for 91.6%.

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[1] *'Injera'*- is a thin round flatbread consumed in much of Ethiopia that uses up more than 50% of the total household energy demand (Kebede and Kiflu, 2014; Mulugeta et al., 2017)

These figures indicate that energy use in Ethiopia is dominated by the household sector, and most of the households live in rural areas, and rural energy use means biomass, but the biomass utilization is traditional and unsustainable. As a consequence, Ethiopia faces complex and multifaceted challenges in its quest for achieving rapid and sustainable development; and energy and environmental security. On the one hand, heavy reliance and unsustainable use of biomass energy is depleting the country's forest resources (Asfaw and Demissie, 2012; Guta, 2012). According to FAO (2015) estimates, Ethiopia lost on average 105, 000 hectares (ha) or 0.8% of its forests per year between 1990 and 2015, a significant proportion of which is directly related to [2]fuelwood collection and charcoal production (Duguma et al., 2019). Biomass is a renewable energy source and the use of biomass for energy is not the problem *per se*, it is the unsustainability of the harvest and traditional nature of the utilization. To such an extent that the projected demand for fuelwood of Ethiopia for 2014 (88.9 million m^3) was ten times as much as the sustainable supply (8.8 million m^3) (EFAP, 1994). This has a direct bearing on forest and land management, biodiversity, and climate-resilience of the country.

On the other hand, the acute shortage and unreliable supply of modern energy services such as electricity is undermining Ethiopia's efforts for rapid and sustained economic growth (Abdisa, 2018; Carlsson et al., 2018). According to a recent report of the World Bank (2019), Ethiopia's economy grew by an average of 9.9% per year between 2008 and 2018, making it one of the fastest-growing economies in Africa. This rapid economic expansion has led to a dramatic surge in demand for energy, with demand for electricity forecasted to grow by 10 - 14% per year between 2012 and 2037 (EEP, 2014). Ensuring access to modern, affordable, and sustainable energy supply is, thus, a sine qua non for Ethiopia to meet its growing energy demand, alleviate poverty, and realize sustainable development. With 85 % of its land degraded to varying degrees, Ethiopia is also highly vulnerable to the negative impacts of climate change (Deressa et al., 2008; Nkonya et al., 2015). As such, increasing the production and utilization of renewable energy and clean cooking facilities is vital to build a climate-resilient economy, mitigate deforestation and reduce the adverse health impacts of traditional and unsustainable use of biomass fuels.

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[2] According to the Ministry of Environment, Forest and Climate Change (MEFCC, 2017a), the major direct drivers of deforestation and forest degradation in Ethiopia are land-clearing for agricultural expansion, fuelwood collection, illegal logging, infrastructure development, and fire.

1.2. Ethiopia's climate-resilient green economy initiative

Fully cognizant of the pressing needs to structurally and fundamentally re-engineer the country's development path including the energy sector, Ethiopia initiated an ambitious Climate Resilient Green Economy Strategy (CRGE) in 2011. The CRGE envisions building a climate-resilient and sustainable economy with the goal of transforming the country to a middle-income status by 2025 (FDRE, 2011). Under the CRGE, Ethiopia intends to cut its net GHGs emissions by 255 Mt CO_2e in 2030, which is a 64% reduction compared to the 'business- as--usual' (BAU) emission level (FDRE, 2011).

Two of the four pillars identified as instrumental in underpinning the climate-resilient green economic development path are the renewable energy and environment/forestry sectors. In view of this, the CRGE gives priority to expanding power generation from the country's large renewable energy resources; and increasing the supply of modern, clean and affordable energy for domestic markets as well as power export to regional markets (FDRE, 2011). Furthermore, the CRGE aims at reducing demand for fuelwood through the distribution of fuel-efficient cooking technologies, and alternative cooking fuels such as electricity, biogas and liquefied petroleum gas. To achieve these strategic objectives, Ethiopia crafted a series of what are known as 'Growth and Transformation Plans' (GTP). During the implementation of the first GTP which lasted from 2011 to 2015, the energy sector had planned to expand the total installed power generation capacity of the country from 2 GW to 10 GW by 2015 (FDRE, 2010). Following a modest achievement in GTP I (4.3 GW by 2015), Ethiopia launched its second Growth and Transformation Plan (GTP II) in 2016, with the energy sector tasked to increase the country's power generation capacity to 17.2 GW by 2020 (FDRE, 2016).

Foremost among the strategies pursued by the government to improve rural access to modern energy and increased energy efficiency are rural electrification through grid expansion; rural electrification through solar PVs; and dissemination of biogas and ICSs. To that end, the Ethiopian government with the technical and financial assistance from international organizations, and participation of the private sector has disseminated a significant number of Solar PV systems, domestic biogas plants, and ICSs over the years. Ethiopia has also embraced the United Nations REED+ mechanism (**R**educing **E**missions from **D**eforestation and forest **D**egradation). REDD+ is an international framework through which developing countries receive financial payments (rewards) for reducing atmospheric concentrations and emissions of CO_2 through improved conservation and management of forests, avoided deforestation and enhanced forest carbon stocks (Phelps et al., 2012). The government of Ethiopia has also taken a few policy measures including the Energy Proclamation No 810/2013, and the 'Public-Private Partnership Proclamation No 1076/2018 (FDRE, 2018). These proclamations aim to improve energy efficiency and conservation, and encourage the participation of the private sector and Public-Private Partnership (PPP) in the country's energy sector development.

1.3. The research problem/knowledge gaps

Whilst the various initiatives, efforts, and policy measures discussed above are expected to increase the access and use of clean and modern energy services and thereby induce energy transition in Ethiopia, very little empirical research has been carried out to date to validate this, particularly in rural areas. Previous works on household energy use and transition in Ethiopia have focused on urban consumers (e.g. Alem et al., 2016; Beyene and Koch, 2013; Gebreegziabher et al., 2012) despite rural households being the largest energy consumers. Few Controlled Cooking Tests (e.g. Dresen, 2014; Gebreegziabher et al., 2018) in rural Ethiopia have shown that the use of ICSs can lead to significant fuel savings compared to traditional stoves. Notwithstanding, substantial knowledge gaps remain concerning the interaction and effects of access to renewable energy sources and technologies (RES & Ts) on rural household energy consumption patterns and transition under the normal rural setting subject to various limiting factors.

Several important questions also remain unaddressed concerning the nexus between access to RES &Ts; and socio-economic development, energy-efficiency, and well-being of rural communities. Moreover, in light of the recent signs of progress in modern energy access in the country; the major drivers, setbacks, and determinants of rural households' energy choices for cooking and lighting purposes have not been thoroughly investigated. Given that more than 85% of Ethiopia's GHGs emission is coming from the agriculture and deforestation/land-use changes –mainly in rural areas (FDRE, 2011), it is important to explore the implications of rural households' access to modern and renewable energy, and improved cooking facilities on the country's CO_2 emissions reduction, mitigation of climate change and sustainable utilization of biomass resources.

2. Objectives, research questions, and hypothesis

2.1. Overall objective

Against this background, the main aim of this thesis was to investigate and empirically analyse the effects of access to modern and renewable energy sources and technologies on rural household energy use patterns, well-being, and the environment in Southern Ethiopia; thereby to contribute to the scientific knowledge and policy-making towards sustainable energy transition in the country and sub-Saharan Africa at large.

2.2. Specific objectives and research questions

1. To synthesize and critically analyse existing evidence on potential environmental impacts of small-scale renewable energy technologies (SRETs) in East Africa

   Q1. What does the scientific evidence suggest about the environmental impacts of SRETs (biogas, ICSs) in the East African region?

   Q2. What are the major barriers to the widespread and efficient use of SRETs?

2. To analyse the current utilization rate, performance, and energy-use impacts of domestic biogas plants in rural southern Ethiopia and draw policy implications

   Q1. What is the current operational status and utilization level of household biogas systems installed hitherto in the study areas (SNNPRS)?

   Q2. Are biogas users consuming significantly lower quantities of woodfuels and kerosene compared with the non-users?

3. To investigate the potential fuel savings, environmental and economic co-benefits of three ICSs: *Mirt*, *Gonziye* and *Tikikil* in rural Southern Ethiopia

   Q1. How much and how significant are the fuel, time, and CO_2 emission savings of rural households from the use of *Mirt*, *Gonziye,* and *Tikikil* stoves?

   Q2. What is the economic effect of adoption (and use) of ICSs to the rural Communities, and its implications to sustainable biomass energy use?

4. To assess and analyse the impacts of rural electrification through solar PV-systems and lanterns in rural southern Ethiopia

   Q1. What is the role of solar PVs and lanterns in improving rural access to basic electricity, and reducing kerosene consumption and expenditures for lighting?

   Q2. How significant is the impact of access to solar lighting on household emissions of black carbon (BC) and CO_2 from kerosene wick lamps?

   Q3. What are the major problems facing rural electrification through solar PVs?

5. To quantify and analyse the current rural household energy use patterns and the share of renewables in the total household energy consumption

   Q1. How much energy does the average rural household consume? And what is the share of energy from renewable and modern sources?

   Q2. Has the rural household reliance on biomass fuels and kerosene declined as a result of access to modern and renewable energy sources and technologies?

   Q3. What is the prospect of energy transition for cooking and lighting in rural (southern) Ethiopia?

6. To empirically analyse the major determinants of rural household energy choices

   Q1. What is the relationship between rural households' cooking fuel choices and their socio-economic and demographic characteristics?

   Q2. What determines rural households' energy choices for lighting?

   Q3. What does the evidence suggest about the energy choice behaviours of rural households and transition towards more sustainable and clean sources?

2.3. Hypothesis

It is hypothesized that households with access to modern and clean energy sources and improved cooking facilities have significantly lower consumptions of traditional biomass and fossil fuels; and a higher probability of energy transition than those without.

The remainder of the thesis is organized as follows. Chapter 3 presents the conceptual and theoretical frameworks used as background for the study. It provides an overview of the relationship between access to RES & Ts, and energy security and transition in the context of developing countries. The fourth chapter describes the study areas, sampling approach, and the methods used for data collection and analysis. Chapter 5 reports and discusses the main findings of papers I – VI. It establishes the evidence-base to answer the research questions and confirm or reject the hypothesis. Finally, Chapter 6 provides major conclusions and policy implications drawn from the studies.

3. Conceptual and theoretical frameworks

3.1. Renewable energy, environment, and sustainable development

Ensuring access to affordable, reliable, sustainable and modern energy for all (SDG-7) is at the heart of the United Nation's Sustainable Development Agenda 2030 owing to its pivotal role in human and economic development, poverty reduction, education, health care and environmental protection (United Nations, 2015). A growing body of scientific evidence indicates that renewable energy and energy-efficient technologies (RES & Ts) present new opportunities for improving energy access and security, socio-economic development, and mitigation of climate change and negative environmental and health impacts of consumption of traditional fuels (Brew-Hammond, 2010; Gielen et al., 2019).

In this thesis, we build on the conceptual framework developed by Sathaye et al. (2011) and Owusu et al. (2016) to construct the inter-linkages between access to renewable/ clean energy and technologies; AND household energy security, economic development and environmental sustainability/GHGs emissions abatement in the developing world.

Energy security:

According to Kruyt et al. (2009) and Valentine (2011), the concept of energy security generally highlights three major aspects of energy supply: availability, affordability, and reliability. Considering the strong causal relationship between energy consumption and economic growth (Apergis and Payne, 2012), securing a reliable and affordable energy supply thus stimulates economic growth. For this reason, globally per capita income is positively and strongly correlated with per capita energy consumption (Chaudhry et al., 2012). For poorly electrified developing countries with abundant renewable energy potential like Ethiopia, renewable energy systems present a cost-effective, reliable, and environmentally friendly means of providing electricity to industries and households. Improved energy security also means reduced imports of fossil fuels and less use of traditional biomass fuels. For the largely unelectrified rural population of Ethiopia in particular, harnessing renewable energy from decentralized and stand-alone solar PV systems, renewable-based mini-grids, and biogas systems could thus diversify the rural energy supply options and increase households' energy security.

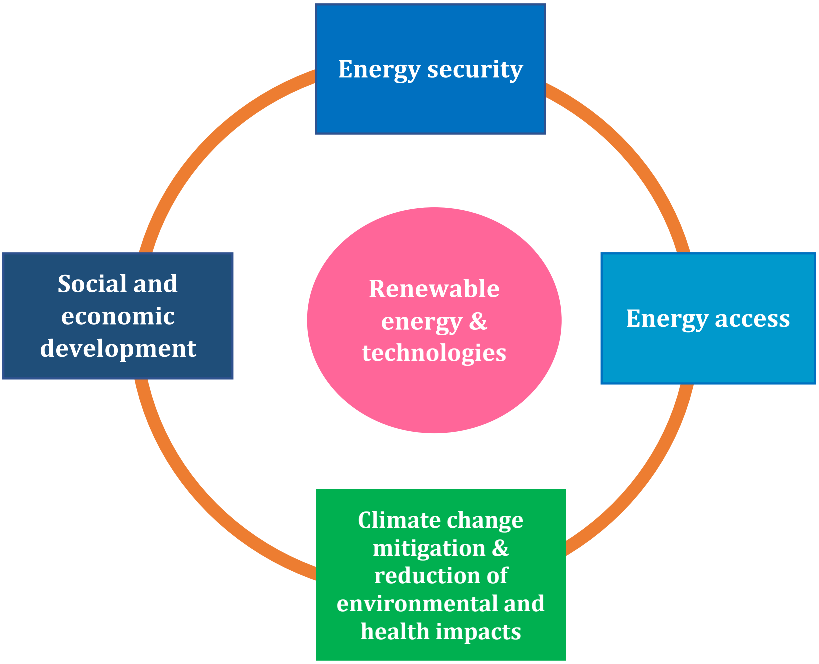

Figure 2. Schematic representation of inter-linkages between RES & Ts; and its energy, economic and environmental effects (based on Owusu et al., 2016)

Energy access:

The United Nations sustainable development goal (SDG–7) underlines that sustainable energy is realized when all its three components: access, efficiency, and renewable energy are met (United Nations, 2015). In this sense, ensuring energy access is concerned with closing the gap in energy access between the poor and the rich, urban and rural areas, as well as ensuring access to clean and energy-efficient cooking technologies. For many countries in SSA including Ethiopia, this could be achieved through tapping renewable energy sources since they are widely distributed across the countries (Brew-Hammond, 2010). For instance, based on extensive research and practical experiences in Senegal, Ulsrud et al. (2018) have noted that with suitable policies and regulations in place, solar mini-grids can provide equitable and affordable electricity access in rural SSA. Likewise, mini-grids based on other renewables (e.g. mini-hydropower plants) can provide energy services to communities that have no or limited access to the grid. Along the same lines, the application of energy-efficient cookstoves can reduce the serious health damages, and climate/environmental effects of traditional and inefficient cooking methods that predominate in much of rural Ethiopia and SSA (Edenhofer et al., 2011).

Social and economic development:

There is ample evidence that social and economic development is strongly correlated with energy consumption (Apergis and Payne, 2012; Chaudhry et al., 2012). Access to renewable energy strengthens this strong association while avoiding the environmental and social cost of GHGs emissions, thus contributing to sustainable development. For instance, a study by Fang (2011) in China indicated that a 1% increase in renewable energy consumption increases the per capita annual income of rural households by 0.444%. Likewise, a recent study by Singh et al. (2019) found that renewable energy production is positively and statistically significantly correlated with economic growth both in developing and advanced economies.

Since renewable energy sources are much less costly for the society in terms of health impacts, environmental degradation, and climate change effects; they are strongly associated with sustainable development (Fang, 2011; Sathaye et al. 2011). For the poor rural communities of SSA, access to modern and reliable energy from renewable sources can, therefore, induce positive social and economic changes by improving education, income generation, job creation, health care, and welfare of the communities. Some other studies, however, have found insignificant but positive relationship between renewable energy consumption and economic growth (Apergis and Payne, 2011; Bhat, 2018).

Climate change mitigation and reduction of environmental and health impacts: Renewable energy sources play a major role in climate change mitigation and reduction of environmental and health impacts associated with GHGs emissions and pollutants from fossil fuels (IPCC, 2014; Sathaye et al., 2011). Studies also show that cooking with modern and clean technologies substantially reduces CO_2 emissions and the formation of black carbon (BC) – a potent global-warming agent with severe health consequences (Grieshop et al., 2011; Lam et al., 2012). Renewable energy sources are hence considered clean energy sources offering ample opportunities to arrest environmental degradation, GHGs emission, and indoor air pollution from solid biomass and fossil fuel-based energy sources (IPCC, 2014; Panwar et al., 2011).

However, renewable energy is not a panacea for all the development and environmental problems facing developing countries. It has its trade-offs. In this regard, Nepal (2012) writes that renewable energy often comes with high investment costs and technological capability challenges, especially for poorer countries. As such, the benefits of renewable energy technologies for under-developed countries heavily depend on the technology and knowledge transfer from developed countries.

3.2. Household energy choices and energy transition process in the developing world: A theoretical perspective

Two strands of theoretical models are often used in the literature to explain household energy choice behaviours and energy transition processes in the developing world: the ‘energy-ladder’ and ‘energy- stacking’ models (Heltberg et al., 2004; Masera et., 2000). The energy-ladder (fuel-switching) model is premised on the microeconomic theory of rational choice and utility maximization (Hosier and Dowd, 1987). The model purports that faced with a range of energy use options, households would imitate the behaviour of a utility-maximising neoclassical consumer; and switch from primitive ‘inferior’ fuels to more modern, expensive, and clean energy carriers as their economic status improves (Barnes and Floor, 1996; Hosier and Dowd, 1987). Climbing up the energy ladder from the bottom to top, this model ranks household energy sources into three levels or rungs: 1) Primitive – comprising of low-quality fuels: fuelwood, agri.-residues, and dung cakes; 2) Transitional – consisting of charcoal, kerosene and coal; and 3) Advanced/modern - electricity, LPG, biogas and other biofuels (Schlag and Zuzarte, 2008).

As illustrated in Figure 3, the energy-ladder model proposes that households ascend the energy ladder by switching from one type of fuel to another as their socio-economic status improves significantly (Leach, 1992; van der Kroon et al., 2013).

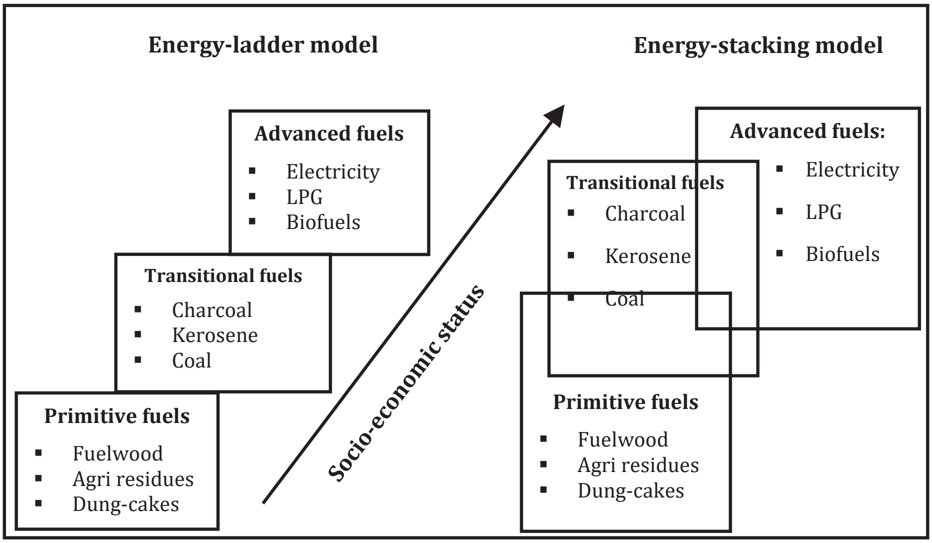

Figure 3. The energy transition process (Based on Schlag and Zuzarte, 2008)

The two main concepts at the core of the energy ladder model are thus ‘a unidirectional linear switching process – leapfrogging – between fuels’ and ‘complete abandonment and replacement of consumption of one type of fuel by another’ – following a significant change in income level. In essence, the model holds the view that household energy choice behaviours and energy transition process is primarily determined by the income of the household and follows a unidirectional linear path, given a set of readily accessible energy sources (Hosier and Dowd, 1987; Leach, 1992).

However, a growing body of empirical evidence suggests that household energy choice and transition process in developing countries is not unidirectional as portrayed by the energy ladder model. According to these studies, rather than simple-switching between fuels (as in the energy–ladder model), households tend to diversify their energy sources and consume traditional fuels alongside modern, and clean fuels regardless of increase in their economic status– what is known as the energy–stacking (multiple fuels use) model (Masera et al., 2000; Mekonnen et al., 2009; van Kroon et al., 2013).

The energy-stacking model argues that household energy choices and transition process in developing countries is an incremental process—instead of leaps—resulting from complex interactions between economic, technological, institutional and socio-cultural factors and capabilities in lieu of a purely income-based unidirectional process (Masera et al., 2000; Murphy, 2001). This model maintains that, 'the fuel-switching process' does not occur as simple disconnected steps, but rather as an intertwined and connected process whereby households create a portfolio (stack) of multiple energy sources and consume modern energy for certain end-uses and traditional fuels for other end-uses depending upon several economic and non-economic factors, preferences and contexts (Msera et al., 2000; van Kroon et al., 2013). However, the model notes that the share of energy from modern sources and traditional fuels in the household energy portfolio can vary across time and socio-economic status (Heltberg 2005; Masera et al., 2000).

The model affirms that faced with readily accessible energy choice options, households diversify their energy use portfolio and use 'multiple fuels' to exploit complementarities among alternative energy options even if their income increases (Nansairo et al., 2011; Narain et al., 2008). This phenomenon is evident from the findings of several studies in rural areas of many developing countries where many well-off households, who could essentially afford clean and modern energy services, were consuming traditional (solid biomass) fuels alongside modern fuels (electricity) to meet their energy requirements (Heltberg, 2005, Mekonnen et al., 2009). For instance, a study by Masera et al. (2000) in rural Mexico showed that as households became wealthier, they began accumulating energy use options from multiple sources instead of linear switching between fuels. In Guatemala, Heltberg (2005) found that modern fuels were used alongside traditional woody biomass fuels by a significant proportion of rural households despite an increase in their income. Nansaior et al. (2011) in Thailand found that although the share of solid biomass fuels in the household energy mix declined following economic development, there was no sharp displacement of traditional biomass fuels by modern energy sources.

Another major drawback of the energy-ladder theory, besides the linear fuel-switching, is the idea that the households' economic status (income) alone is the primary driver of energy choice behaviours. In light of this, several studies have demonstrated that apart from income, many other factors are also used as a basis for household decision making over which fuels to use (Mekonnen et al., 2009; Heltberg, 2005). These studies show that household decision over energy choice involves consideration of a wide range of factors including availability of fuel, reliability of modern energy supply, access to alternative and modern energy sources, technological capability, institutional barriers, government support and subsidy, living standards, educational status, and compatibility to cooking cultures and habits among others (Mekonnen et al., 2009; Pundo and Fraser, 2006).

For instance, a study by Narain et al (2008) in rural India found that the consumption of fuelwood increased with forest biomass availability irrespective of the income level of the households. Whereas Campbell et al. (2003) in rural Zimbabwe found that access to electricity was a major driver for household transition to clean energy. A similar study by Guta (2014) in Ethiopia found that household fuelwood use increased with increase in household economic status, and declined with increase in household electricity use and fuelwood scarcity. Based on the evidence from these studies, it can be concluded that although income plays a pivotal role, it may not be the sole factor determining rural households' energy choices and energy transition process in developing countries.

4. Materials and methods

4.1. Study sites and sampling approach

This research was carried out primarily in four selected rural districts of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia. The four districts are *Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya.* The region lies between Latitudes 4°43' – 8°58' North and Longitudes 34°88' – 39°14' East. Administratively, the SNNPRS is divided into 14 zones (provinces) and 4 special *woredas* (districts) consisting of a total of 137 rural districts and 22 urban administrations. The districts are further subdivided into *kebeles* (neighbourhoods), the smallest administrative units of Ethiopia. The total population of SNNPRS was estimated to be 19. 2 million in 2017, of which approx. 90% were rural inhabitants composed of 2,743,502 households in 3,709 *kebeles* and 10% were urban dwellers made up of 367,493 households in 324 *kebeles* (CSA, 2013).

Out of the total 9 regional states in Ethiopia, SNNPRS was selected for this study for three important reasons. First, it is one of the four regional states in the country where alternative and renewable energy technologies deployment first began. Second, the region is home to some of Ethiopia's last remaining natural forests; and third, it is characterized by diverse natural resources endowment, livelihoods and agro-climatic conditions that may affect household energy choice, use and the transition process.

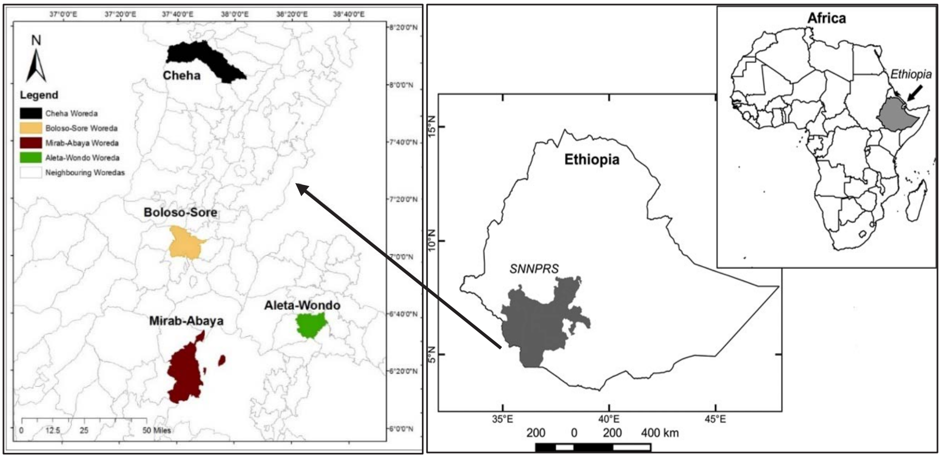

Fig 4. Location map of the SNNPRS and study districts (*woredas*)

A multi-stage stratified random sampling approach was used to select sample districts and households required for the study. In the first stage, 23 rural districts (from the 137 rural districts in the SNNPRS) – where renewable energy technologies intervention has been active over the last decade – were identified based on data from the regional Mines and Energy Agency and the Central Statistical Agency of Ethiopia (CSA, 2013). The 23 districts were then clustered into three groups as highland, midland, and lowland based on their agro-climatic conditions. The justification for the clustering of the districts into agro-climatic zones is to capture the potential effects of agro-ecology dependent factors on household energy sources, consumption patterns, and technology use.

Subsequently, two districts from the highland, one from the midland and one from the lowland were randomly selected. Two districts were selected from the highland because over half of the 23 districts identified fell in this category. Accordingly, Aleta-wondo with a mean altitude of 2037 meters above sea level (m.a.s.l.) and Cheha with a mean altitude of 2130 m.a.s.l. were selected from the highland; and Boloso-sore with a mean altitude of 1877 m.a.s.l and Mirab-abaya with a mean altitude of 1193 m.a.s.l. were selected from the midland and lowland strata respectively. The estimated total population of Aleta-wondo district in 2017 was 187,957 consisting of 33, 738 households and that of Cheha district was 122,770 composed of 24,554 households. The estimated total population of Boloso-sore in 2017 was 187,558 comprised of 36,410 households and that of Mirab-abaya district was 90, 508 composed of 12,784 households (CSA, 2013).

In the second stage, a representative sample size for the study was estimated at 95% confidence level, 4% precision level (for large sample size and smaller allowable error between sample estimates and true population values) and p = 0.5 (for unknown population proportion to generate the largest sample size) following Cochran (1977).

$$N = \frac{(z^2 \boldsymbol{\alpha}/_2)\,(p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\,.\,(0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:

N= is the desired sample size
P = 0.5 is the assumed population proportion expected to have access to renewables
e= 0.04 is the desired precision (or margin of error) at 4%
$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size for the research was calculated at 660. This total sample size was subsequently distributed to the four sample districts by using the probability proportional to the household size (PHS) method. Hence, of the total 660 sample households, 207 were allotted to Aleta-wondo, 224 to Boloso-sore, 151 to Cheha, and 78 to Mirab-abaya districts. In the third stage, three *Kebeles* (wards) were chosen randomly in each district and the sample size allotted to each district was distributed to the three *kebeles* by using the PHS method. Finally, a random selection of sample households was made from a complete list of all households in each *Kebele* by using a simple lottery method.

4.2. Data collection methods

4.2.1. Systematic Review (Paper I)

A systematic review approach was employed to select, critically analyse, and synthesize existing empirical evidence on the potential environmental impacts of the use of small-scale renewable energy technologies (SRETs) in the context of East Africa. To that end, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) flow diagram was used for searching and extracting data following Moher et al. (2009). The SRETs included in the review were domestic biogas systems, solar home systems (SHS) and improved biomass cookstoves (ICS), First, the key research questions of the paper were formulated. This was followed by a comprehensive literature search and selection of a total of 659 eligible studies (both journal articles and grey literature).

The literature search was mainly focused on the four most populous nations in the East African region namely: Ethiopia, Kenya, Tanzania, and Uganda. Eligible scientific studies were then subjected to thorough screening and objective evaluation for relevance and quality based on a set of inclusion and exclusion criteria following the guideline outlined by Bowler et al. (2010). Finally, full-text evaluation and extraction of quantitative and qualitative data was conducted from 88 studies; of which 47 were quantitative and 41 were qualitative. Based on the data extracted from these studies, the potential woodfuel savings and GHGs emission reductions of each country from the biogas plants and ICSs disseminated up until 2015 were estimated by using the FAO (2002) charcoal to dry-wood and the IPCC (1996) fuelwood to [3]CO_2e emission conversion factors.

4.2.2. Cross-sectional household surveys (Papers II - VI)

A large part of the primary data in this research was collected through a comprehensive cross-sectional study (survey) of sample households in the four selected rural districts of the SNNPRS comprising a total of 12 *kebeles*. As indicated in the sampling procedure, a total of 660 sample households; 358 from the highland category (207 in Aleta-wondo and 151 in Cheha), 224 from the midland (Boloso-sore district) and 78 from the lowland

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[3] When an emission estimate is the sum of several GHGs expressed as the equivalent amount of CO_2, it is referred to in CO_2 equivalents, often abbreviated as CO_2e (IPCC, 1996).

(Mirab-abaya) were randomly selected. Accordingly, a cross-sectional household survey was conducted using semi-structured questionnaires that were administered through a face-to-face interview by the researchers and a total of 16 field assistants (trained data enumerators). The survey questionnaires were designed based on the objectives of the research and review of relevant literature.

To ensure that the survey instruments and the data collected are reliable, representative and valid; several considerations were made during the designing of the questionnaires and other data collection instruments following the guidelines outlined by Groves and Heeringa (2006). The most important considerations made included identifying the characteristics of the target population and ensuring that the questions represent the diverse demographic and socio-economic classes in the population, and generate the desired outcome. Other important points considered include the use of multiple (cross-validating) measures, use of local measurement units, use of local language, appropriate wording, sequencing, and balancing of open and closed questions.

For this purpose, preliminary studies were conducted in each study district prior to the questionnaire designing, and information was gathered on various research variables. This was followed by a systematic development of the questionnaires and pretesting on 24 randomly selected households in the study areas. The results from the pre-test were used to improve and fine-tune the survey instruments. The actual survey was finally carried out from January to December of 2018 in such a way that sample households in each district were randomly assigned to the four seasons in Ethiopia to offset potential effects of seasonality on fuel availability and household energy use.

The data gathered from the household surveys include demographic and socioeconomic characteristics; energy sources; cooking and lighting fuels and consumption quantities; fuel prices and expenditures, time spent on fuelwood collection and cooking; connection to the grid and adoption of renewable energy technologies (biogas, solar and ICSs) and current state of utilization; capacity ratings; financing sources; and markets as well as the setbacks and barriers to the use of modern and clean energy sources.

4.2.3. Direct field assessments and consumption measurements (Papers II - VI)

To accurately establish household energy use patterns and minimise the impact of self-report response bias; direct field studies, and energy consumption measurements were conducted alongside the surveys. The direct field investigations and assessments were made on the current state of use and performance of 32 household biogas systems, 137 solar home systems (SHSs) and [4]PicoPVs, and 133 ICSs. This was accompanied by direct measurement of the actual energy consumptions of 96 households (≈ 15% of the total samples) from within the 660 sample households for two consecutive weeks. The 96 households for the direct energy consumption measurements were selected randomly from the four study districts such that 24 were biogas owners, 24 ICS users, and 24 solar PV/lantern users. The remaining 24 were non-users of biogas, solar PV/lantern or ICSs. The data collected from the direct consumption measurements were used to establish energy consumption benchmarks and triangulate the self-reported survey data.

4.2.4. Key informant interviews and group score ranking (Papers II - VI)

A total of over 100 key informant interviews were conducted to gather information on various topics of the research. The key informants were selected purposively owing to their first-hand knowledge and experience in rural household energy use trends, access, and promotion of clean technologies. The key informants included: community leaders, household heads, kebele and district level energy technology promoters; researchers; fuelwood, charcoal and kerosene sellers; biogas masons, ICS producers, NGOs, solar PV importers and distributors, and technicians. In addition, the Direct Matrix Score Ranking (DMR) Method was applied to explore problems facing the utilization and operation of biogas plants in the study areas with a total of seven focus group discussions.

4.2.5. Track-record data and secondary sources (Papers II - VI)

Official data on the number of biogas digesters installed and inventory reports of their current operational status were obtained from the energy and technology promotion offices of each district. In addition; valuable secondary data were gathered from several reports and documents of various international organizations as well as from a number of published and unpublished research works.

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[4] PicoPVs are small Photovoltaic systems with a power output of up to 10Wp, mainly used for lighting, charging mobile phones and/or powering radios

4.3. Data analysis methods

4.3.1. Descriptive and inferential statistics (Papers I - VI)

Descriptive statistics and cross-tabulations were used to summarize the characteristics of sample households and analyse the adoption rates and distribution patterns of small-scale renewable energy technologies in the study areas. Inferential statistics including independent sample t-tests, Pearson's Chi-square ($\chi2$) tests, biserial correlation tests, univariate analysis of variance (ANOVA), multivariate analysis of variance (MANOVA), and multiple linear regression (MLR) were used to test the significance of differences in mean values of important explanatory variables between renewable energy/technology user and non-user households as well as to determine relationships between renewable energy technologies use/impact and relevant explanatory variables.

4.3.2. Household energy consumption estimations and analysis (Papers I - V)

To analyse household energy consumptions from the various energy sources, separate quantifications were made for each fuel type based on the data collected from the direct measurements and household surveys. To that end, the most common local fuel supply modes and units were first identified for each fuel type. Afterwards, sufficient samples were taken for each fuel supply mode (local unit) from local open markets, retailers, and consumers; and the average weights and volumes were established in standard units. Finally, the average weekly and monthly consumption of biomass fuels and kerosene per household were calculated by using these average values and the survey data. Electricity consumption of households were estimated based on monthly electric utility bills. The daily biogas consumptions of households were estimated based on data from the direct field studies and methods suggested by IRENA (2016, p. 14). Energy use from solar PVs was estimated by using Nelson and Starcher (2015) equation.

4.3.3. Household fuel, time and CO_2e emissions savings analysis (Papers I - IV))

Based on the survey data and the energy consumption analyses, the average fuel savings of technology users were calculated in comparison with the consumption of non-users for each technology. These fuel savings were translated to energy cost savings by using local market prices and shadow prices, to analyse direct economic effects. Based on the fuel savings estimated, CO_2e emission reductions from the use of biogas and ICSs were estimated using the IPCC (2006, 1996] conversion factors of fuelwood from dry weight to CO_2e. The CO_2 emission reductions from the use of SHSs and PicoPVs were estimated based on conversion factors for traditional kerosene wick lamps following Chaurey and Kandpal (2010). Household's fuelwood collection and cooking time savings from the use of ICSs were estimated for each stove by using the data collected from the actual kitchen cooking observations, interviews of fuelwood collectors, and data from the surveys.

4.3.4. Cost-benefit analysis (Paper III)

A Cost-benefit analysis (CBA) was used to measure the net benefits and welfare effects of the three most commonly used ICSs for the local community in the study areas. The CBA was conducted following the methods used by Habermehl (2007, 1999). The main criterion used to measure the economic efficiency (impact) of the ICSs were Net Present Values (NPV), Benefit-Cost Ratio (BCR) and Internal Rate of Return (IRR). Market prices, shadow prices, and shadow wages were used to monetarily value the economic benefits from avoided fuel costs, avoided fuelwood collections, fuelwood collection and cooking time savings, and CO_2e emissions reductions due to the use of ICS.

4.3.5. Econometric analyses (Papers IV & VI)

The binary logistic model: The binary logistic regression model was used to analyse factors influencing household's adoption decision of solar PVs. The binary logit model is often used to examine the relationship between a discrete dependent variable Y and one or more explanatory variables X. Binary logit models apply the maximum likelihood estimations to determine the likelihood of occurrence of an event from a dichotomous outcome of a dependent variable (Y) (Greene, 2008). The dependent variable 'Y_i' in this case (the probability that a rural household adopts a solar product) thus takes the value of $Y_i = 1$ if the household owns /uses solar PVs or $Y_i = 0$ otherwise. Following Greene (2008), the probability that household *i* adopts solar PV can be specified as:

$$P_i = \Pr[Y_i = 1] = \frac{exp(\alpha + \beta X)}{1 + exp(\alpha + \beta X)} \qquad (2)$$

Where P_i is the probability that household i adopts solar PV, X_i is a vector of explanatory variables for household i, α and β represent parameter estimates of the logit model

The Multivariate Probit Model (MVP): The multivariate probit (MVP) model was used to analyse factors influencing household energy choices for lighting. The Chi-square *(χ^2)* test for independence of households' energy choices for lighting (kerosene, electricity, solar, biogas, and dry-cell batteries) showed that the choices are correlated with each other (p=0.000). The appropriate econometric model to analyse correlated multivariate binary outcomes is thus the Multivariate Probit (MVP) model (Edwards and Allenby, 2003; Golob and Regan, 2002). This is because, given a set of energy choice alternatives, the MVP model estimates the influence of explanatory variables on the probability of choice of each of the energy options jointly while allowing the error term to be freely correlated (Golob and Regan, 2002). Accordingly, five commonly used lighting energy sources of sample households were identified and set as binary dependent variables: 1) kerosene, 2) electricity, 3) solar, 4) biogas, and 5) batteries. For each lighting energy source, the household is faced with a binary decision (1= usage of the particular fuel, or 0= otherwise). Following the works of Ali et al. (2019) and Behera et al. (2015), the MVP model used to analyse the factors determining the lighting energy choice decisions of sample households, with five dependent variables, $y_1, \ldots, y_5$ was formulated as:

$$\begin{aligned} y_i &= 1 \text{ if } \quad \beta_i X' + \varepsilon_i > 0 \\ &\text{and} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (3) \\ y_i &= 0 \text{ if } \quad \beta_i X' + \varepsilon_i \leq 0 \qquad i = 1,2,\ldots 5 \end{aligned}$$

where X is a vector of the explanatory variables; β_1, β_2, β_3, β_4, and β_5 are conformable parameter vectors and ε_1, ε_2, ε_3, ε_4, and ε_5 are random errors distributed as a multivariate normal distribution with zero mean and unitary variance.

4.4. Profiles of sample households and Normality of data

Out of the total 660 sample households determined for the study, 605 completed the survey. The data from the remaining 55 were either incomplete or hugely inaccurate when cross-validated and hence excluded. The overall response rate was, thus, 91.70%. As shown in the summary statistics of the sampled households in Table 1, out of the 605 households that completed the survey, 189 (31%) were selected from Aleta-wondo district, 204 (34%) from Boloso-sore, 134 (22%) from Cheha and 78 (13%) were from Mirab-abaya districts. In terms of gender, of the total 605 households studied, 84.13% were headed by males and the remaining 15.87% were headed by female heads.

Table 1. Summary statistics of sample households

Explanatory variables	Statistic	Study sites (districts) Aleta-wondo	 Boloso-sore	 Cheha	 Mirab-abaya	Mean (SE) (N = 605)
Number of sample households	Num	189	204	134	78	605
Gender of HH head; If Male	Num	162	181	108	58	509
Age of HH head	Mean	50.65	43.95	49.71	51.53	48.30 (10.92)
Education level of HH head	Mean	5.86	4.62	3.97	3.55	4.73 (3.77)
Total household size*	Mean	6.76	7.00	4.34	6.29	6.24 (2.38)
Family members < 15 years	Mean	3.21	3.63	1.62	1.64	2.80 (1.84)
Total landholding size, ha	Mean	0.53	0.88	0.65	0.74	0.70 (0.64)
Total cattle heads size	Mean	3.06	3.44	2.85	5.83	3.50 (2.36)
Gross cash income/year (ETB)	Mean	28358	16579	17184	38123	22155 (22350)
Walking distance to wood source (round trip), minutes	Mean	52.8	49.6	42.8	152.8	62.4 (75.2)
Walking distance to market, (round trip), minutes	Mean	106.8	108.4	104	100.4	105.2 (35.2)
HHs connected to the grid	Freq (%)	77	18	40	59	194 (32%)
HHs with access to credit	Freq (%)	104	44	30	34	212 (35%)
HHs with ICSs	Freq (%)	38	20	34	41	133 (22%)
HHs with biogas plant	Freq (%)	12	8	7	5	32 (5.3%)
HHs with solar PV product	Freq (%)	37	26	63	11	137 (22.64%)

Source: own survey, 2018; Numbers in parenthesis are standard errors (SE)
*Simple counting of total members of the family (not in adult-equivalent)

The average age of household-heads was 48.30 years, and the average educational level of household-heads measured in terms of the number of years of schooling completed was 4.73. The average family size was 6.24 persons per household. On average, there are 2.8 persons per household under the age of 15 years. The average landholding size per household is about 0.7 hectares (ha) with the highest holding (0.88 ha) in Boloso-sore and the lowest (0.53 ha) in Aleta-wondo. The average cattle heads size is 3.50 per household, with the highest cattle holding (5.83 heads) in Mirab-abaya and lowest (2.85 heads) in Cheha districts. The average [5]gross cash income per household was estimated to be Ethiopian Birr (ETB) 22,155, roughly US$ 815 (in August 2018) per year. However, household income varies greatly across the four study districts with higher incomes observed in the largely cash-crops growing districts of Mirab-abaya (ETB 38,123) and Aleta-wondo (ETB 28,358) compared with the mostly food crops producing districts of Cheha (ETB 17,184) and Boloso-sore (ETB 16, 579) respectively.

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[5] Gross annual cash income was calculated by identifying the major income sources of each sample household and accounting the total cash collected by the household from these sources during the last 12 months (2017 to 2018 period)

With respect to occupation (the major source of livelihoods), generally, households are engaged in multiple occupations. That being the case, 32% stated cash-crops growing such as coffee, khat (*C. edulis*), and banana as their primary occupation; 26% stated food crops production mainly *Enset (E. ventricosum),* root-crops and cereals; and 24% are engaged in crop and livestock mixed-farming. In contrast, 13% make their living from Off-farm activities including daily labour and collection of forest products (fuelwood, timber, and non-timber products), and 5 % pursue small-scale private business.

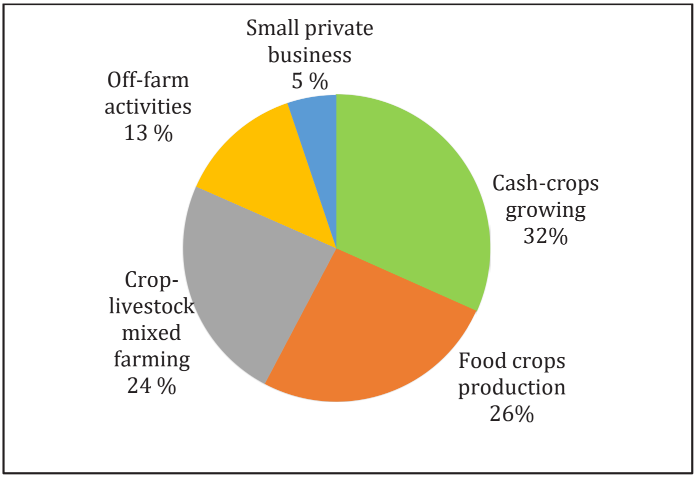

Figure 5. Distribution of sample households by primary occupations (source of income)

Yet, there are large variations in terms of the importance of these occupations as a major source of livelihoods between the four districts. Many households in Aleta-wondo and Mirab-abaya were found to be cash-crops growers compared to Cheha and Boloso-sore. The average round-trip walking distance between households' home and the common wood source (forests and woodlands) was 62.4 minutes but varies between the shortest 42.8 minutes in Cheha district and the longest 152.8 minutes in Mirab-abaya district. The average walking distance between the households' home and the local market was 105.2 minutes (round-trip) with variations between the shortest 100.4 minutes for households in Mirab-abaya and the longest 108.4 minutes in Boloso-sore. About 35% of the households have [6]access to credit services. But there is a notable variation in access to credit facilities among households in the four districts as can be seen in Table 1.

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[6] In this study, 'households with access to credit' refers to those households who have an approved credit application or those that have received a loan from local (government and private) formal credit supplier institutions during the last 10 years.

About 32% of the sample households are connected to the national grid (Ethiopia's main electricity supplier). However, a stark disparity was observed in access to electricity between the four districts. So much that, more than 75% of the sample households in Mirab-abaya district are connected to the grid while only 8.8% of households in Boloso-sore have a connection to the grid. Whilst this average 32% electricity coverage is in line with the World Bank's recent report (2017) of 31% for rural households in Ethiopia, the high rate of electricity coverage in Mirab-abaya district could be due to its proximity to Arba-minch city and the major power line crossing the district.

With regard to biogas, a total of 32 biogas owners were found from the random sample of 605 households in the four study districts. This corresponds to 5.3% of the sample households. However, as will be discussed in paper II, a significant fraction of the biogas plants constructed in the study areas are currently either non-functional or have low production efficiency. The summary statistics in Table 1 also illustrate that 22% (a total of 133) of the sampled households own at least one type of ICSs for cooking, baking, or a combination of purposes. The four types of ICSs most commonly used in the area were: *Mirt* 'Injera' baking stove (without chimney), *Gonziye* multi-purpose (cooking and Injera baking) stove, and *Tikikil* and *Lakech* cooking stoves. Except for *Lakech,* which is a charcoal-burning stove, all the other stoves are wood burning.

Similarly, 22.6% of the sample households (a total of 137) own at least one type of solar PV technology or solar lantern for lighting. However, a considerable variation exists in solar lighting use between the four districts. It was found that 47% of the households sampled in Cheha district own solar products whereas only 12.7% of the households in Boloso-sore have solar lights. The most commonly used solar PV systems are: Pico-PVs (lanterns and simple LED - Light-emitting diode systems) with PV capacity of up to 10 peak watt ([7]Wp); followed by solar home systems (SHSs) with PV capacity between 10 and 100 Wp; and institutional solar home systems with PV capacity of more than 100 Wp. To determine whether the sample data set is drawn from a normally distributed population (hence standard parametric statistical methods can be used) we conducted the Shapiro–Wilk test of Normality. The results indicated that the data collected for most of the variables (in each group) were approximately normally distributed with p-values between 0.113 and 0.770. However, some data were non-normally distributed.

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[7] Watt peak (Wp) is the maximum electric power produced by a solar panel under Standard Test Conditions (STC).

5. Main results and discussions

5.1. Paper I: Potential environmental impacts of small-scale renewable energy technologies (SRETs) in East Africa: A systematic review

Findings from the systematic literature review indicated that between 2005 and 2015, about 15,000 domestic biogas plants in Ethiopia; 17, 500 in Kenya; 12, 000 in Tanzania and 6,100 in Uganda had been constructed. During the same period, an estimated 3.3 million ICSs in Ethiopia; 1.3 million in Kenya; 1.2 million in Tanzania, and 0.561 million in Uganda had been distributed. By contrast, about 40, 000 SHSs in Ethiopia; 445,000–470,000 in Kenya; 65,000 in Tanzania and 26,000 in Uganda had been disseminated between 2005 and 2015. As a result, the new access to cleaner energy and fuel- efficient biomass cooking stoves has enabled households to significantly reduce their woodfuel consumptions. According to the studies reviewed; a single biogas plant could on average save 4.719 tons of woodfuel in Ethiopia, 3.65 tons in Kenya, 5.376 tons in Tanzania, and 1.61 tons in Uganda per household per year. Likewise, the studies reviewed showed that the use of a single ICS could save on average 0.918 tons of woodfuel in Ethiopia, 1.35 tons in Kenya, 1.15 tons in Tanzania, and 0.53 tons in Uganda per household per year.

The findings from these studies show that the use of biogas technology has led to partial energy transition at the household level from a dominantly wood fuel-based to a new energy mix where the share of clean biofuel is significant. The substitution of fuelwood and charcoal by cleaner energy from biogas has reduced firewood collection and tree-felling for domestic energy, thus mitigating deforestation and land degradation at local levels. The decrease in consumption and burning of woodfuels as a result of the use of biogas and ICSs contributes to reduced emissions of CO_2 and associated health risks of women and children from the indoor air pollution.

Notwithstanding the sizable positive effects observed at household and local levels, the study finds that the impact of SRETs in curtailing fuelwood consumption and mitigating deforestation and GHGs emissions at national levels appears limited. Our conservative estimates based on the data extracted from the studies reviewed showed that if all the biogas plants and ICS disseminated till 2015 in the four countries are operational and used uninterruptedly, they have the combined potential of saving the consumption of 3.10 Mt of wood and reducing the emission of 5.67 $MtCO_2e$ per year for Ethiopia; 1.82 Mt of woodfuel and 3.33 $MtCO_2e$ for Kenya; 1.45 Mt of woodfuel and 2.65 $MtCO_2e$ for Tanzania; and 0.31 Mt of woodfuel and 0.562 $MtCO_2e$ for Uganda per year.

The above results suggest that, at national and regional levels, the potential impacts of SRETs distributed in substituting and curbing the woody biomass energy consumption and GHGs emissions of each country is limited. Apparently, the estimated wood-savings and CO_2e emission reductions due to biogas and ICS disseminated in Ethiopia could only avoid 5.2% of the [8]total woody biomass consumption (48.6 Mt) for domestic energy, and 3.8% of the total GHGs emissions (150 $MtCO_2e$) of the country per year. In Kenya, the potential energy savings from the biogas plants and ICS disseminated could only offset 4.5% of the total national biomass energy demand (40.5 Mt). The estimates for Tanzania suggest that the expected woodfuel savings from the biogas plants and ICS account for only 7.2% of the 20 Mt of woodfuel consumed in the country per year. For Uganda, the biogas plants and ICSs disseminated are expected to offset only about 1% of the 40 Mt total biomass energy consumed in the country per year.

Overall, the findings from paper I showed that despite the considerable household level positive effects, the impact of SRETs in curbing the heavy dependence and unsustainable use of solid biomass fuels and the associated forest and land degradation at national and regional levels remains limited. Unleashing the potentials of SRETs and achieving broad-based positive impact at national and regional levels however entails addressing some critical challenges through providing adequate policy priority for household level small-scale renewable energy technologies, building the institutional and technical capacity of local and national SRETs implementing agencies; introducing innovative financing systems to promote the uptake of SRETs; improving the operational practice of users, regular monitoring of SRETs utilization, creating adequate awareness and experience sharing platforms, and strengthening inter-sectoral integration and policy alignment between implementing ministries including the private sector.

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[8] According to the Ethiopian biomass energy strategy and action plan (MoWIE, 2014] an estimated 60 Mt of biomass is consumed in the country per year for domestic energy purposes, of which 81% (48.6 Mt) is used as woodfuel for Injera baking, cooking, heating, and other domestic purposes.

5.2. Paper II: Analysing household biogas utilization and impact in rural Ethiopia: Lessons and policy implications for sub-Saharan Africa

Findings from the direct field examinations and survey data analysis revealed that of the total 605 households studied, only 32 (5.3%) owned domestic biogas plants. In terms of the current state of functionality, it was found that of the 32 biogas plants investigated, only 21 (65.6%) were functional during the field study while the remaining 11 (34.4%) were non-functional or have failed beyond repair. Most of the digesters constructed are fixed dome model (adaptation of the Nepalese GGC-2047 design) and the majority (90%) are of 6m^3 digester capacity. The main reason for the preference of 6m^3 digester over other sizes is perhaps its suitability to local cattle holding (feedstock availability) and household sizes of the rural households in the areas, besides its cost-effectiveness.

The average quantity of biogas produced and consumed from a 6m^3 functional plant was estimated at 0.61 m^3/day. This corresponds to a total biogas consumption of 223 m^3 per user household per year. From the field studies, it was confirmed that all the biogas produced is used up within 24 hours; implying that the daily biogas production rate is the same as the daily consumption rate. Based on this annual biogas consumption, it was estimated that the current level of biogas use could substitute the consumption of 631.7 kg of fuelwood for cooking and 25 litres of kerosene for lighting per household per year. However, comparing this average daily biogas consumption of 0.61 m^3 per digester with an average production capacity of a 6m^3 plant (1.6 - 2.4 m^3/day) in developing countries (Eshete et al., 2006; Schwarz, 2007), reveals that the current production efficiency of digesters constructed in the study areas is roughly between 25% and 38%.

To further investigate the effects of biogas use on household energy consumption, we analysed the data collected from the direct energy consumption measurements of both biogas user and non-user households. The results indicated that the average fuelwood consumption of biogas users (4665 kg/year) is lower than the non-users (5225 kg/year) by 560 kg/year. This means that biogas users could avoid approx. 10.7% of their annual fuelwood consumption by using biogas. This accords to our earlier finding from the daily biogas consumption estimate that biogas user households could save on average 631.7 kg of fuelwood per year. Yet, results from the multiple linear regression analysis and t-tests of mean total energy consumptions of biogas users and non-users showed that the effect of biogas use on household fuelwood and kerosene consumption was statistically insignificant. Contrary to the significant impacts observed at household level in paper I, findings from this empirical study showed that the effect of biogas use in reducing the solid biomass fuels consumptions and improving the energy mix of biogas users towards cleaner sources was marginal. Indeed, biogas users have reduced their fuelwood and kerosene consumptions, but the magnitude of impact or difference created by the biogas use remains insignificant. The disparity between the evidence found in paper I and the results from this empirical study might be explained by the fact that most of the previous works reviewed in paper I were based on purposively selected fully functional digesters whereas the digesters examined in this study were drawn from a random sampling and hence include many poorly performing digesters relative to the sample size.

In light of the findings from the field studies, we analysed the track-record data on the current operational status of the 657 biogas plants installed in the four districts between 2011 and 2017. The result (Figure 6) showed that of the total 657 digesters installed, only 337 (51.3%) were functional in 2018 while the remaining 320 (48.7%) were non-functional. This demonstrates that the challenge for improving biogas technology use in Ethiopia stems not only from the low rate of adoption and diffusion of the technology but more importantly also from the failure of many of the digesters installed and the low production efficiency of those that are functional. As a result, biogas user households in rural Ethiopia continue to depend on fuelwood and kerosene - as main energy sources for cooking and lighting respectively– in quantities almost as much as the non-users.

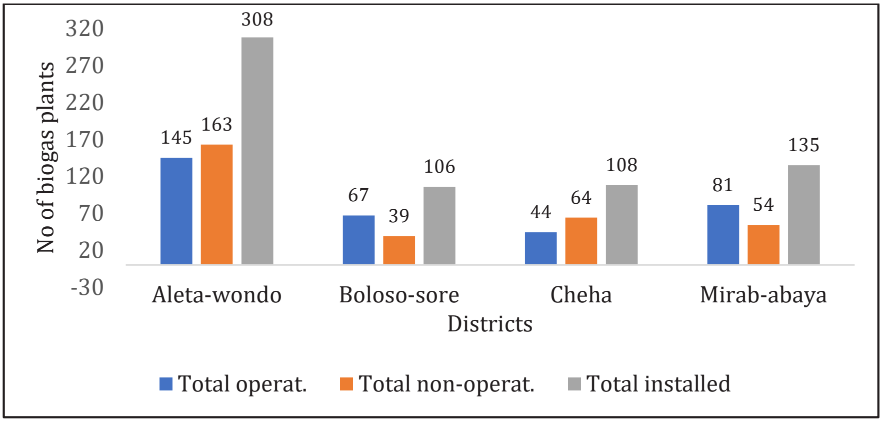

Figure 6. Current operational status of biogas plants installed between 2011 and 2017 in the four districts (based on panel data from district energy offices, 2018)

5.3. Paper III: Analysis of fuel savings, economic and environmental effects of improved biomass cooking-stoves in rural Ethiopia

In this study, we analysed the potential fuel savings, CO_2e emissions reductions, and net economic benefits of three most widely used improved biomass cooking stoves (ICSs): *Mirt*, *Gonziye,* and *Tikikil* in rural southern Ethiopia. The results showed that about 22% of the survey households currently own at least one type of ICSs. This may suggest that roughly one in five rural households in the study areas currently uses ICSs for cooking and/or baking purposes. However, it was also discovered that almost all (99%) of the households surveyed still use traditional three-stone open fire stoves. This confirms that even when ICSs are used, they are often combined with traditional stoves to fulfil all household needs. In terms of rate of uptake, *Mirt* stove is adopted by 12.4%, *Tikikil* by 3.64%, and *Gonziye* by 2.98% of the survey households.

A separate analysis of the fuel savings of the three ICSs compared with the traditional open-fire tripod indicated that the use of a single *Mirt* stove could lead to a net fuelwood savings of 1.72 tons, *Gonziye* 1.94 tons and *Tikikil* 2.08 tons per household per year. Assuming the net calorific value of fuelwood (air-dried) at 15 MJ/kg (Hall et al., 1994) and emission intensity of 109.7 g CO_2e/MJ in traditional tripod stoves (Bhattacharya and Salam, 2002; IPCC, 2006); the above fuelwood savings translate to an estimated CO_2e emission reduction of 2.82 tCO_2e for *Mirt*, 3.19 tCO_2e for *Gonziye,* and 3.43 tCO_2e for Tikikil per year. The estimates for household fuelwood collection, and cooking/baking time savings due to these ICS showed that a *Mirt* stove user household could save a total of 62.40 hours, *Gonziye* user 96.00 hours, and *Tikikil* user 86.40 hours per year.

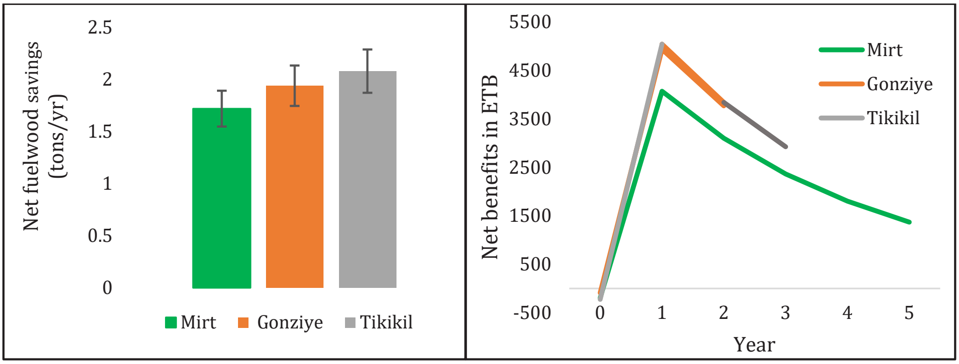

Figure 7a. Total net fuelwood savings (tons/yr) of each stove; figure 7b cash flow of net economic benefits from each stove in ETB.

To further examine the causal relationship (effect) between ICSs use and consumption of cooking fuels, we calculated the biserial correlation coefficient (r_b). The result showed that household fuelwood consumption is negatively and significantly related to ICS use with a correlation coefficient of $r_b = -0.63$; p-value = 0.00. This indicates that the significantly lower quantity of fuelwood consumed by ICS users compared to non-users is highly likely due to the fuelwood savings from ICSs, *ceteris paribus*. According to the Ministry of Environment, Forest and Climate Change of Ethiopia (MEFCC, 2017b), by the end of 2017, about 15 million ICSs have been disseminated in the country. Assuming that 10 million of the 15 million ICSs distributed (67%) are currently functional (given these three ICSs are the most widely used ICSs), the estimated fuelwood savings suggest that Ethiopia could save 17.2 to 20.8 Mt of wood per year from using ICSs. This implies that Ethiopia could cut back its biomass energy consumption of 60 Mt/year (MoWIE, 2014) by 25% to 30% from the use of ICSs. In terms of GHGs emissions, the results imply that Ethiopia could avoid the emissions of 28 Mt to 34 MtCO_2e per year if 10 million of the 15 million ICSs distributed are currently in active use. This amounts to 18% - 22% reduction in the country's total annual GHGs emissions of 150 Mt CO_2e (UNDP, 2011).

The results of the cost-benefit analysis (see Figure 7) indicate that all the three ICSs have positive Net Present Values (NPV) implying that investment in any of these stoves is economically viable and provides substantial net economic benefits to the community compared to the status quo (use of traditional tripod). According to our findings, the use of a single *Mirt* stove could provide a net economic return of ETB 12 512 (US$ 460) during its 5 years lifespan; *Gonziye stove* provides NPV of ETB 8 614 (US$ 317) during its two years lifespan; and *Tikikil* stove offers NPV of ETB 11 583 (US$ 426) during its three years economic lifespan. The benefit-cost ratios (BCR) of the three stoves were calculated at 20.1:1, 42.0:1, and 19.6:1 for *Mirt*, *Gonziye,* and *Tikikil* respectively.

Overall, the study finds that the three ICSs, if regularly used, significantly improve the energy-efficiency and welfare of rural communities while reducing the CO_2 emission and biomass energy consumption of Ethiopia considerably. The findings highlight that the use of ICSs is a viable option and an essential component of the solution for reducing the increasing pressure on forest resources for domestic energy, and balancing the demand for fuelwood with the sustainable yield. The implication is that Ethiopia and many other solid biomass-energy dependent developing countries need to promote the large-scale and sustained use of ICS through providing incentives, and soliciting funds from global carbon markets for emission reductions achieved through ICSs.

5.4. Paper IV: Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from Southern Ethiopia

In this particular paper, we examined the energy, economic, and environmental effects of rural electrification with Solar PV systems and lanterns in the study areas. Most of the data were collected from direct field assessment of 137 SHSs/PicoPVs used by sample households. The findings showed that the uptake and usage of solar PV systems in rural southern Ethiopia is growing fairly rapidly. According to our results, the current rate of uptake of solar lighting systems (SHSs and lanterns) is approx. 22.6%, suggesting that roughly one in five rural families in the study areas has access to solar lighting. From the distribution of the solar systems assessed by rated power of peak watt (Wp) in Figure 8, about 63% of solar users own simple Pico-PVs (and LED lanterns) with PV capacity of less than 10 Wp; 30% own SHSs with PV capacity of 10 to 40 Wp; 5% own SHSs with PV capacity of 41 to 100 Wp; and about 2 % own SHSs with PV capacity over 100 Wp. The main reason for the preference of PicoPVs to larger capacity systems, as explained by the solar user households, is the high cost of larger capacity SHSs and conversely, the affordability, ease of portability, and simplicity of use of the simple Pico-PV systems.

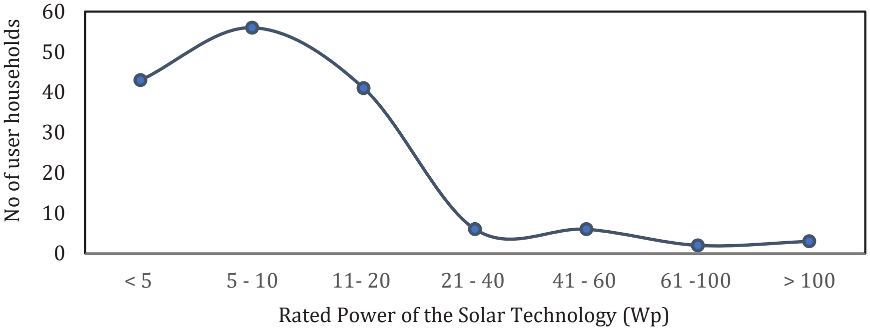

Figure 8. Distribution of solar technologies in the study area by power generation capacity

Analyses of the quantitative and qualitative data collected with respect to the benefits of the solar solutions revealed that the primary benefit of solar PVs is the access to clean, safe, and quality lighting and basic electricity; and the associated reduction in kerosene consumption for lighting. Based on our estimates, monthly kerosene consumptions of a household drops on average from 4.46 L to 0.47 L when grid-electrified; and to 0.82 L when [9]solar-electrified compared to non-electrified (neither grid nor solar) households. As a result, a solar-user household on average saves about 43.68 L (81.6%) of kerosene consumption for lighting compared to non-electrified households. As the results of the ANOVA analysis in Table 2 show, solar electrification has resulted in significant energy substitution (P =0.00) and partial transition for lighting from kerosene-based towards clean and renewable energy source, solar power.

Table 2. ANOVA results of mean monthly kerosene consumption (L) of household groups by type of electrification

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Grid-electrified	194	91.33	0.470	0.855
Solar-electrified	137	112.55	0.821	2.858
Non-electrified	274	1221.95	4.459	1.593

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2224.63	2	1112.31	677.17	8.6E-15	3.01
Within Groups	988.83	602	1.6425			
Total	3213.472	604				

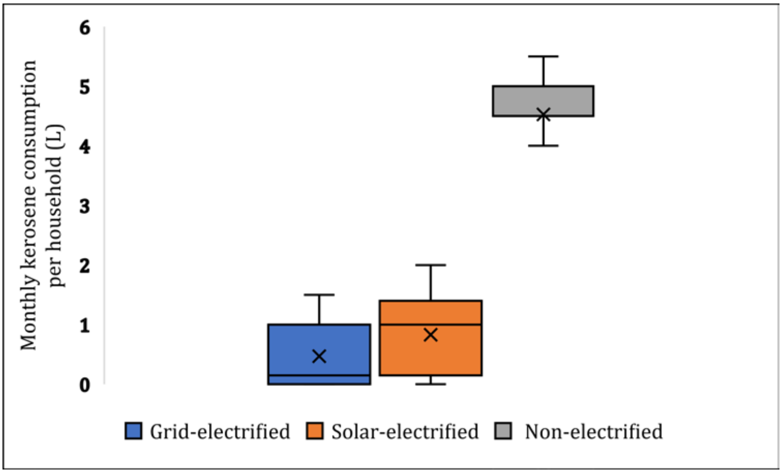

Figure 9. Box plot of mean monthly kerosene consumption by type of electrification

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[9] Solar-electrified, in this study, refers to rural households that are primarily using SHSs and/or PicoPVs (LED lanterns) for domestic lighting, mobile phone charging, powering radios and/or running small businesses.

In line with the findings of Ulsrud (2020), it appears that decentralized small-scale solar PVs were comparable, if not more suitable, to the grid in providing affordable electricity access and reducing kerosene consumption even in areas that are connected to the grid. However, as the mean kerosene consumption values in Figure 9 indicate, neither solar nor grid-electrification has led to complete abandonment of kerosene use for lighting. This is, in part, attributable to the supply-side problems in a sense that electricity supply in rural Ethiopia is highly unreliable with frequent outages and intermittency problems due to power shortages. On the other hand, the continued dependence of solar users on kerosene is largely due to the low electricity generation capacity of the solar systems.

In terms of energy costs, the study finds that the monthly lighting fuel expenditure of a household falls on average by ETB 89.7 (57%) when grid-electrified; and by ETB 107.55 (68%) when solar-electrified compared to non-electrified households. This monthly fuel expenditure saving corresponds to an estimated annual energy expenditure savings of ETB 1084.76 for grid-electrified and ETB 1285.20 for solar-user households. The access to electricity from the solar PVs has enabled households to reduce their mobile charging costs by ETB 480 - 720 per year. This means a solar-electrified household could save ETB 1765 - 2005 (US$65 - 75) per year from reduced energy costs and avoided mobile charging expenses. Based on our market studies, the above monetary saving can recover the total (capital and installation) cost of a 10Wp SHS in less than 2.5 years.

Beyond the access to basic electricity, it was also estimated that a solar user household could abate on average the emissions of 2.72 kg of Black Carbon (BC) and 107 kg of CO_2 per year compared to non-electrified ones. This reduces the exposure of rural families to diseases associated with traditional wick lamps. According to some SHSs users, access to solar electricity has helped them create new income-generating activities as well as increase incomes of existing small-businesses, although some previous works had found no evidence of the direct economic impact of SHSs (Feron, 2016; Wamukonya and Davis, 2001). Empirical results from the binomial logit model revealed that household income level, distance to market, and access to credit financing are the major factors positively and significantly influencing the adoption of solar products. The results have important policy implications on the role of access to credit, and distance to (solar) market centre, in addition to income, in improving rural access to solar lighting.

Overall the evidence from this study highlighted that decentralized small-scale solar PVs are providing rural households in Ethiopia with access to basic electricity and improved quality of life. Moreover, SHSs and lanterns do help in abating the emissions of GHGs by directly replacing the use of kerosene for lighting. Considering the high capital cost of grid expansion to most rural and off-grid areas of Ethiopia, the findings present strong case for promoting the wide-scale use of larger capacity solar PVs with greater financial incentives and subsidies. Tapping this potential nevertheless requires tackling major hurdles and problems facing the sustainability and efficacy of the use of solar products. The major problems identified include poor-quality and counterfeit solar products in black markets with low prices. A related problem is the lack of after-sales maintenance and technical support service from solar suppliers which in turn is due in large part to the purchase of most of the products from black markets with no warranty. There also lies a major problem with the limited supply of quality-verified solar products largely due to protracted import process and lack of foreign currency. As a result, even when the quality-verified solar products reach the local market, their price is inflated. This is exacerbated by the limited access to credit financing for low-income households.

5.5. Paper V: Household energy consumption patterns and the share of renewable and modern energy sources in rural southern Ethiopia

This paper was aimed at analysing the current patterns of rural household energy use and the prospects of energy transition towards modern and clean fuels in the study area in light of the recent signs of progress in modern energy access in Ethiopia. The study finds that about 97% of the households depend on traditional biomass fuels as primary energy sources for cooking; of which fuelwood accounted for 90.7%. By contrast, 1.98% use biogas, and 1.16% use electricity for cooking. Analysis of household energy sources for baking '*Injera'* and '*Kocho'* (Ethiopian bread) – which constitute more than 50% of the households' energy consumption (Mulugeta et al., 2017) – indicated that 99% of the households use solid biomass fuels, dominantly fuelwood. Concerning lighting energy nonetheless, 50% of the sampled households use kerosene, 29% electricity, 19% solar power, and 1.98% biogas as primary energy sources for lighting. Although these fuels were identified as primary energy sources, however, it was found from the direct energy consumption measurements and kitchen cooking studies that many of the households use multiple fuels for cooking, baking, and lighting. On another note, the use of kerosene and dung cakes for cooking and baking was found to be very limited.

Accounting of the household energy consumption from the different fuel types revealed that on average a rural household in the study areas consumes 5021.8 kg of fuelwood per year. According to our findings, about 55% of the households collect fuelwood from 'open access' state and communal forests, and woodlands despite these resources are 'protected' by law. In congruence with the findings of Gebrehiwot et al. (2016) sizable (25%) fraction of the sampled households reported gathering fuelwood from their farmlands and homegardens; whereas 11.25% reported buying fuelwood from local markets and 8.5% do a combination of collecting and buying. Nonetheless, from the analysis of household energy consumption measurements, it was evident that the average quantity of fuelwood collected from communal/state forests per household per year was 4,248 kg (84.60%) compared to the fuelwood collected from own homegardens and farmlands 525 kg (10.46%) while the quantity purchased was approx. 248 kg (4.94%) of the total 5021.8 kg consumed per household per year. Given that most of the fuelwood supplied to local markets is 'freely' collected from state and community forests, the results imply that nearly 90% (4496.8 kg) of the total household demand for fuelwood is met by these forests. This renders state and communal forests most vulnerable to deforestation from the rising demand for woodfuel, effectively creating an energy-environment dual crisis.

The average annual consumptions of the households for other fuels were estimated at 532.5 kg of agri-residues, 73.3 kg of charcoal, 17.5kg of dung-cakes, 30 litres of kerosene, 7.78 m^3 of biogas, 182 kWh of electricity and 4.76 kWh of solar power. By converting the energy consumptions from the different fuels into Megajoules (MJ) and aggregating the results; the total annual energy consumption of a household was estimated to be 87, 172 MJ. Of which, 75, 327 MJ is derived from fuelwood; 7667 MJ from agri.-residues; 2126.6 MJ from charcoal; 157 MJ from dung-cakes; 1064 MJ from kerosene; 657 MJ from electricity; 156 MJ from biogas and 17.1 MJ from solar. These results indicate that of the total household energy consumption of 87, 172 MJ/year; more than 97% (85, 278 MJ) is derived from traditional biomass fuels, of which fuelwood takes the lion's share of 86.4% (75,327 MJ). In contrast, petroleum products (kerosene) accounted for 1.22% (1064 MJ) whereas energy obtained from modern and renewable sources (electricity, biogas, and solar power) combined constituted only to approx. 1% (829.5 MJ) (see Figure 10).

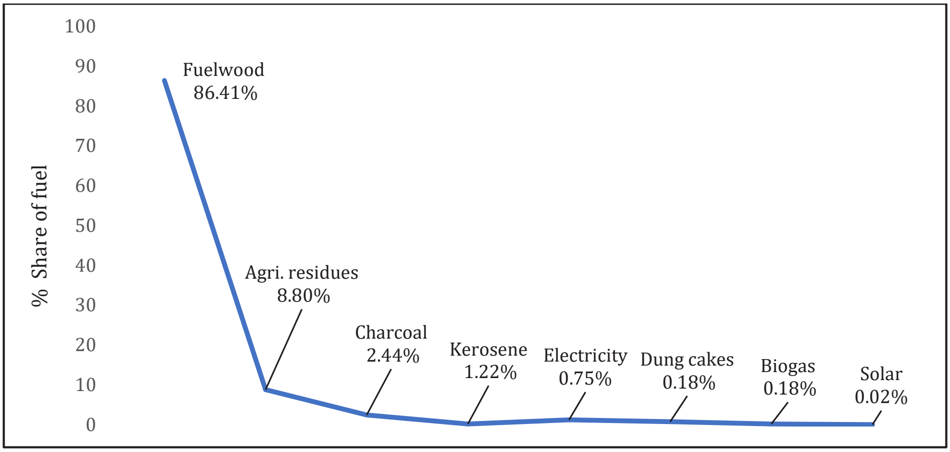

Figure 10. Percent share of the different fuels in the total household energy consumption

The findings confirm that traditional biomass fuels (mainly fuelwood) remain the most dominant and the largest energy sources of rural households in Ethiopia particularly for cooking and baking end-uses, constituting more than 97% of the total household energy consumption. As such, this study finds no evidence of significant energy substitution or slowing down of the heavy reliance on traditional biomass fuels for cooking and baking. On the other hand, energy from modern and renewable sources accounted for approx. 1% of the total household energy use. Most of this energy is used for lighting. Despite its invisible share, the study finds that energy from renewable and modern sources has led to significant energy substitution and partial transition from kerosene-oil towards clean lighting fuels. Yet, many of the households that are connected to the grid or that have adopted solar lighting systems still consume a significant amount of kerosene and dry-cell batteries as back-up and alternative lighting energy sources. This could be, in part, due to major supply-side problems including frequent power outages and unreliability of electricity supply, and the limited capacity of the solar PVs/lanterns.

The implication is that solid biomass fuels will likely remain the primary energy sources of households in rural Ethiopia and sub-Saharan Africa for decades to come. Given that over 97% of the rural household energy consumption is used for cooking and baking end-uses, Ethiopia needs to critically address the household demand for biomass fuels through developing sustainable and diversified bio-energy sources, more efficient and affordable cooking and baking technologies, and decentralized renewable hybrid energy systems, besides the current efforts of improving rural access to grid electricity.

5.6. Paper VI: Determinants of household energy choices in rural sub-Saharan Africa: An example from southern Ethiopia

In view of the findings in papers I-V, in paper VI we analysed the determinants of rural household's energy choices for cooking and lighting separately by using the data from the household surveys and direct observational studies. Pearson's non-parametric Chi-square ($\chi 2$) test and Multivariate probit (MVP) model were used to analyse the data. The results indicated that about 40% of the sample households utilize a mix of multiple fuels for cooking; whereas 60% depend solely on one type of fuel as the main energy source for cooking, of which fuelwood is principal. This shows that while fuelwood remains the primary cooking fuel, it is occasionally combined with other fuels for complementarity advantages. The most common cooking fuel portfolio of the households was fuelwood and agri-residues, and the maximum number of cooking fuels combined is four.

The Chi-square tests revealed that household's cooking fuel choices are statistically and significantly associated with the household size, distance to wood source (or access to 'freely available' wood), geographic location, main occupation, and income. Conversely, grid connection, gender, age, and education level of the household were found to be not strongly related to the cooking fuel choices. The results are in contrast to the findings of previous studies in other developing countries (Heltberg, 2004; Rahut et al., 2014; Makonese et al., 2018) which indicated that younger, more educated and female-headed households with access to electricity are more likely to choose clean cooking fuels.

Empirical results of the multivariate analysis revealed that households' energy choices for lighting are significantly influenced by their income level, location, education level, household size, landholding and cattle-heads size, distance to market, and road access. Wealthier and more educated households residing near road networks were found to be more likely to choose clean lighting sources such as electricity and solar. By contrast, poorer households residing in distant villages use kerosene and dry-cell batteries. This shows that with increase in the household income, education, and access to renewable energy sources; the probability of use of clean and modern cooking and lighting energy increases. As such, the share of clean and modern fuels in the energy portfolio of higher-income households was relatively large compared to the traditional biomass dominated energy mix of poorer households.

However, high-income level and grid-connection have not led households to completely replace traditional cooking and lighting fuels with modern ones. Instead, with increase in income and access to modern energy sources, households continued to use traditional biomass and fossil fuels alongside modern ones. This pattern concurs to the energy-stacking (multiple fuels use) model of energy transition as opposed to the energy-ladder model of complete fuel-switching with increase in household income level. However, this conclusion of 'energy-stacking behaviour' should be interpreted with caution since the absence of complete fuel-switching (full-fledged transition) is, in part, attributable to important supply-side problems. Foremost among these are limited access to modern energy services, severe shortage and unreliability of electricity supply, malfunctioning of biogas plants, high-cost entailment of electric cooking and *Injera*-baking appliances, and widespread inefficiencies in modern energy distribution and use. As a result, even when a household is connected to the power grid, lack of electric cooking appliances, frequent power outages, and insufficient electricity supply make the use of electricity difficult for the household. On the other hand, the energy shortage for solar users stems mainly from the limited capacity and low quality of solar panels, low battery capacity, intermittency of power generation, and lack of maintenance services.

Another major finding of this study is the significant influence of geographic location or district on the household's choice of energy sources by affecting the income, educational status, access to modern energy sources, and availability of alternative fuels. In Boloso-sore district where the average annual income of a household is the lowest, households may prefer to use kerosene than purchase solar PV as they may not afford the high cost. Conversely, the use of solar PVs is highest in Cheha district partly due to better diffusion of solar products as a result of the well-established solar market. This signifies that the success of rural household energy transition also greatly depends on location-specific variables and the degree to which these variables are addressed in the energy planning. Overall, findings from this study have highlighted that household energy transition in the context of rural SSA is complex and non-linear. As such, while income remains a key factor, several non-income factors also play important role in determining households' choice and transition of cooking and lighting energy. Hence, policymakers and energy planners in Ethiopia and SSA at large may need to take into account these diverse factors when designing energy policies and interventions in rural areas.

6. Concluding remarks and implications

The present thesis investigates and empirically analyses the energy, environmental and socio-economic effects of access to modern and renewable energy sources and energy-efficient cookstoves, and the associated changes in household energy use patterns and energy transition in rural Ethiopia. Our findings from six separate but interconnected studies showed that except for biogas, household use of modern and clean energy such as electricity and solar power; and energy-efficient cooking technologies is increasing. In contrast, the use of household biogas technologies was found to be very low and many of the digesters constructed are either non-functional or are performing very poorly.

In terms of impact, results from our empirical studies highlighted that the recent efforts of the Ethiopian government to improving rural access to modern and clean energy may have led to two differing outcomes. On the one hand, the increased access and use of electricity (90% from hydropower), solar PVs and to lesser extent biogas, has diversified the rural households' energy use options and led to significant energy substitution and partial transition from kerosene-based towards a new lighting energy portfolio where the share of electricity and solar power is significant. This energy transition for lighting, however, does not follow a unidirectional leapfrogging. Rather, it appears to concur with the energy-stacking (multiple fuels use) model. The use of improved cookstoves (ICS) has significantly reduced households' fuelwood consumption. This contributes to the sustainability of biomass utilization and the national GHGs emissions abatement. The economic return of ICS was significant, improving the well-being of rural communities.

On the other hand, the share of renewable and modern energy sources in the household energy mix for cooking and baking is negligible. Traditional solid biomass fuels –mainly fuelwood– are still the dominant energy sources of the rural households for cooking, and baking purposes which constitute the bulk (more than 97%) of the total household energy use. This means that substantive energy transition for cooking and baking in the short-term is farfetched. The implication is that woody biomass fuels will remain the primary energy source of rural households in Ethiopia and much of SSA at least for the foreseeable future. This necessitates innovative approaches and effective mechanisms to address the increasing demand for woodfuels as well as to improving the supply and use of modern and renewable energy sources for cooking and baking.

At the core of the marginal share of energy from modern/clean sources and inefficient use of biogas technologies lie a range of setbacks and problems that can be summarized as 1) lack of prudent and enabling policy frameworks and strong institutional capacity; 2) shortage and unreliability of supply of modern energy services; 3) high capital cost of renewable energy technologies and electrical cooking and baking appliances; 4) lack of market-driven technologies dissemination approaches, and poor feasibility studies. 5) Lack of access to sufficient credit financing and incentives to make the technologies more affordable to the rural poor; 6) lack of after-sales maintenance services. 7) limited awareness and technical know-how among the households on basic applications and repair of the technologies 8) poor-quality and counterfeit products, 9) undeveloped market systems and 10) lack of proper regulations, monitoring, and follow up.

In terms of policy implications, the thesis provides new insights on many fronts. First, there is strong evidence on the significant effects of clean lighting energy sources and hence strengthening the current endeavours of rural access to electricity and solar PVs is critical. Second, the effect of access to renewable energy sources on the household use of woody biomass fuels for cooking and baking is marginal. Therefore, in the short and medium-term, traditional biomass-energy dependent countries like Ethiopia need to decisively address the rural households' demand for biomass energy particularly for cooking and baking as much as the current emphasis is on large-scale power generation and rural electrification. Policy options, to this end, comprise the development of more sustainable biomass energy sources and utilization strategies including large-scale state and private forest plantations for domestic energy use; promoting investments in bio-fuels, diversification of bio-energy sources; improving energy utilization efficiency; and developing decentralized renewable hybrid energy systems (e.g. mini-grids). Third, the evidence for the positive impacts of ICSs is strong. Hence, incentivizing and prompting large-scale production, dissemination and utilization of energy-efficient cooking/baking technologies as well as availing electrical cooking appliances at affordable prices is key.

Future researches areas may include modelling future scenarios of household energy use and CO_2 emissions in light of progress in access to electricity, solar, and ICS use in rural SSA. Another important research area is on noble approaches and energy systems for improving renewable energy security and optimization of synergies between clean energy access, gender-equality, environment, and development in rural SSA.

7. References

Abdisa, L.T. (2018). Power outages, economic cost, and firm performance: Evidence from Ethiopia. Utilities Policy, 53(C):111-120.

Alem, Y., Beyene, A.D., Köhlin, G., Mekonnen, A. (2016). Modelling Household Cooking Fuel Choice: A Panel Multinomial Logit Approach. Energy Economics, 59 (C): 129-137.

Ali, A., Rahut, D.B., Mottaleb, K.A., Aryal, J.P. (2019). Alternate energy sources for lighting among rural households in the Himalayan region of Pakistan: Access and impact. Energy & Environment, 30(7).

Apergis, N., Payne, J.E. (2012). Renewable and non-renewable energy consumption-growth nexus: Evidence from a panel error correction model. Energy Econ, 34: 733–738.

Apergis, N., Payne, E. (2011). Renewable and non-renewable electricity consumption–growth nexus: Evidence from emerging market economies. Applied Energy, 88(12): 5226-5230.

Asfaw, A., Demissie, Y. (2012). Sustainable Household Energy for Addis Ababa, Ethiopia. Consilience: The Journal of Sustainable Development, 8: 1-11.

Bailis, R., Drigo, R., Ghilardi, A., Masera, O. (2015). The carbon footprint of traditional woodfuels. Nature Climate Change, 5(3).

Barnes, D.F., Floor, W.M. (1996). Rural energy in developing countries: a challenge for economic development. Annual Rev. of Energy Environment, 21: 497-530.

Behera, B., Rahut, D.B., Jeetendra, A., Ali, A. (2015). Household collection and use of biomass energy sources in South Asia. Energy, 85:468-480.

Beyene, A.D., Koch, S.F. (2013). Clean fuel-saving technology adoption in urban Ethiopia. Energy Economics, 36: 605-613.

Bhat, J. (2018). Renewable and non-renewable energy consumption—impact on economic growth and CO2 emissions in five emerging market economies. Environmental Science and Pollution Research, 25(12).

Bhattacharya, S.C., Salam, P.A. (2002). Low greenhouse gas biomass options for cooking in the developing countries. Biomass and Bioenergy, 22: 305 – 317.

Bowler, D.E., Buyung-Ali, L.M., Knight, T.M., Pullin, A.S. (2010). A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health, 10:456.

Brew-Hammond, A. (2010). Energy access in Africa: Challenges ahead. Energy Policy, 38: 2291–2301

Campbell, B.M., Vermeulen, S.J., Mangono, J.J., Mabugu, R. (2003). The energy transition in action: urban domestic fuel choices in a changing Zimbabwe. Energy policy, 31: 553-562.

Carlsson, F., Demeke, E., Martinsson, P., Tesemma, T. (2018). Cost of Power Outages for Manufacturing Firms in Ethiopia: A Stated Preference Study. Working Paper in Economics No. 731, University of Gothenburg, Sweden.

Chaudhry, I.S., Safdar, N., Farooq, F. (2012). Energy Consumption and Economic Growth: Empirical Evidence from Pakistan. Pakistan Journal of Social Sciences, 32(2): 371-382.

Chaurey, A., Kandpal, T.C. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. Renew. Sustain. En. Rev., 14: 2266– 2278.

Cochran, W.G. (1977). Sampling Techniques, Wiley, New York.

CSA. (2013). Federal Democratic Republic of Ethiopia, Central Statistical Agency, Population Projection for All Regions at Wereda Level from 2014 – 2017. Addis Ababa. https://www.academia.edu/30252151/Federal_Democratic_Republic_of_Ethiopia_Central_Statistical_Agency_Population_Projection_of_Ethiopia_for_All_Regions_At_Wereda_Level_from_2014_2017(Accessed 03.03.19).

Deichmann, U., Meisner, C., Murray, S., Wheeler, D. (2011). The economics of renewable energy expansion in rural Sub-Saharan Africa. Energy Policy, 39(1): 215-227.

Deressa, T., Hassan, R., Ringler, C. (2008). Measuring Ethiopian farmers' vulnerability to climate change. FPRI Discussion Paper No 00806. International Food Policy Research Institute.

Dresen, E., ... Müller, R. (2014). Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. Land 3(3):1137-1157

Duguma, L.A., …., Bernard, F. (2019). Deforestation and Forest Degradation as an Environmental Behavior: Unpacking Realities Shaping Community Actions. Land, 8 (26).

Edenhofer, O., ..., von Stechow, C. (2011). Renewable Energy Sources and Climate Change Mitigation. Cambridge: Cambridge University.

Edwards, Y. D., Allenby, G. M. (2003). Multivariate analysis of multiple response data. Journal of Marketing Research, 40:321–334.

EEP. (2014). Power Sector Development: Electricity Demand Forecast. Ethiopian Electric Power EEP, 2014. https://pubs.naruc.org/pub.cfm?id=537C14D4-2354-D714-511E-CB19B0D7EBD9 (Accessed 24.05.19).

EFAP. (1994). Ethiopian Forestry Action Program (EFAP): Final report Vol. II- The Challenges of Development: Ministry of Natural Resources Development and Environment Protection, Addis Ababa.

Eshete, G., Sonder, K., Heegde, F. (2006). Report on the feasibility study of a national programme for domestic biogas in Ethiopia. SNV 2006. http://www.bibalex.org/Search4Dev/files/338849/172350.pdf(Accessed 03.01.19).

Fang, Y. (2011). Economic welfare impacts from renewable energy consumption: The China experience. Renew. Sustain. Energy Rev., 15: 5120–5128.

FAO. (2015). Global Forest Resources Assessment 2015: Country Report Ethiopia. Food and Agriculture Organization of the United Nations. FAO, Rome, Italy. http://www.fao.org/3/a-az209e.pdf (Accessed 12.07.19)

FAO. (2002). Charcoal production and use in Africa: What future? Food and Agriculture Organization of the United Nations, FAO, Rome, Italy. Unasylva, 211 (53).

FDRE. (2018). Federal Democratic Republic of Ethiopia. A proclamation to provide for the public-private partnership. Federal Negarit Gazetta, No. 1076. Addis.

FDRE. (2016). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan II (GTP II). National Planning Commission; Addis Ababa. http://www.lse.ac.uk/GranthamInstitute/law/the-growth-and-transformation-plan-gtp-ii/ (Accessed 27.04.19)

FDRE. (2011). Federal Democratic Republic of Ethiopia, Ethiopia's Climate-Resilient Green Economy Strategy (CRGE) Addis Ababa, Ethiopia. https://www.undp.org/content/dam/ethiopia/docs/Ethiopia%20CRGE.pdf (Accessed 04. 01.19)

FDRE. (2010). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan I (GTP I). Ministry of Finance and Economic Development. Addis Ababa. http://extwprlegs1.fao.org/docs/pdf/eth144893.pdf (Accessed 27.04.19)

Feron, S. (2016). Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. Sustainability, 8:1326.

Foell, W., Pachauri, S., Spreng, D., Zerriffi, H. (2011). Household cooking fuels and technologies in developing economies. Energy Policy, 39: 7487–7496.

Gebreegziabher, Z., ..., Toman, M. (2018). Fuel savings, user satisfaction, and demand for improved biomass cook stoves: Evidence from a controlled cooking test trial in Ethiopia. Resource and Energy Economics, 52: 173-185.

Gebreegziabher, Z., Mekonen, A., Kassie, M., Kohlin, G. (2012). Urban Energy Transition and Technology Adoption: The Case of Tigrai, Northern Ethiopia. Energy Economics, 34(2): 410-418.

Gebrehiwot, M., Elbakidze, M., Lidestav, G., Kassa, H. (2016). From self-subsistence farm production to Khat: driving forces of change in Ethiopian agroforestry homegardens. Environmental Conservation, 1:1-10.

Gielen, D., ..., Gorini, R. (2019). The role of renewable energy in the global energy transformation. Energy Strategy Reviews, 24: 38-50.

Golob, T.F., Regan, A.C. (2002). Trucking industry adoption of information technology: a structural multivariate discrete choice model. Transp Res Part C: Emerg Technol, 10:205–228.

Greene, W.H. (2008). Econometric Analysis. 6th Edition, Pearson Prentice Hall.

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

Groves, R.M., Heeringa, S.G. (2006). Responsive design for household surveys: tools for actively controlling survey errors and costs. Journal of the Royal Statistical Society, 169 (3): 439–457.

Guta, D.D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. Energy Policy, 75: 217-227.

Guta, D.D. (2012). Assessment of Biomass Fuel Resource Potential And Utilization in Ethiopia: Sourcing Strategies for Renewable Energies. Int Journal of Renewable Energy Research, 2(1).

Habermehl, H. (2007). Economic Evaluation of the Improved Household Cooking Stove Dissemination Program in Uganda. GTZ, Household Energy Program- 2007. http://www.hedon.info/docs/CostBenefitsUganda-v02.pdf (Accessed 2.1.19)

Habermehl, H. (199). The Economics of Improved Stoves. Guide to micro- and macroeconomic analysis and data assessment. 2nd edition. German Agency of Technical Cooperation (GTZ) Eschborn, Germany.

Hall, D.O., Rosillo-Calle, F., Woods, J. (1994). Biomass utilization in households and industry—Energy use and development. Chemosphere, 29: 1099–1119.

Heltberg, R. (2005). Factors determining household fuel choice in Guatemala. Environment and Development Economics, 10: 337–361

Heltberg, R. (2004). Fuel switching: evidence from eight developing countries. Energy Econ, 26:869–87.

Hosier, R.H., Dowd, J. (1987). Household fuel choice in Zimbabwe: an empirical test of the energy ladder hypothesis. Resources and Energy, 9 (4): 347–361.

IEA. (2018a). World Energy Outlook 2018. International Energy Agency, IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2018 (Accessed 12.5. 19).

IEA. (2018b). Energy statistics Ethiopia 1990 – 2016. International Energy Agency (IEA). https://www.iea.org/statistics/?country=ETHIOPIA&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES (Accessed 28.06.19)

IPCC. (2014). Energy Systems. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report, IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf (Accessed 12.01.19)

IPCC. (2006). Guidelines for National Greenhouse Gas Inventories, Volume 2.2—Stationary Combustion, Intergovernmental Panel on Climate Change. http://www. ipcc-nggip.iges.or.jp/public/2006gl/vol2.html (Accessed 2. 4 .19)

IPCC. (1996). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/report/revised-1996-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (Accessed 20. 04 .19)

IRENA. (2016). Measuring small-scale biogas capacity and production. International Renewable Energy Agency (IRENA), Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Statistics_Measuring_small-scale_biogas_2016.pdf (Accessed 20.05.19).

Kebede, D., Kiflu, A. (2014). Design of Biogas Stove for Injera Baking Application. Int. Journal of Novel Research in Engineering and Science, 1(1); 6-21.

Khan, B., Singh, P. (20179. The Current and Future States of Ethiopia's Energy Sector and Potential for Green Energy: A Comprehensive Study. Int Journal of Engineering Research in Africa, 33:115-139.

Kruyt, B., van Vuuren, D.P., de Vries, H.M., Groenenberg, H. (2009). Indicators for energy security. Energy Policy, 37(6): 2166-2181.

Lam, N. L., ...Bond, T.C. (2012). Household Light Makes Global Heat: High Black Carbon Emissions from Kerosene wick Lamps. Environmental Science & Technology, 46(24): 13531- 13538.

Leach, G. (1992). The energy transition. Energy Policy, 20 (2): 116–123.

Lemma, M. (2014). Power Africa Geothermal Roadshow: Ethiopian Electric Power Strategy and Investment Division, The Ethiopian Electric Power (EEP). https://geothermal.org/Annual_Meeting/PDFs/Mekuria%20Lemma%20Geothermal.pdf (Accessed 05.01.19)

Makonese, T., Ifegbesan, A.P., Rampedi, I.T. (2018). Household cooking fuel use patterns and determinants across southern Africa: Evidence from the demographic and health survey data. Energy & Environment, 29 (1).

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

MEFCC. (2017a). Federal Democratic Republic of Ethiopia; Ministry of Environment, Forest and Climate Change (MEFCC); Environmental and Social Management Framework (ESMF). http://documents.worldbank.org/curated/en/649851491297581422/pdf/113993-EA-P124074-Box402899B-PUBLIC-Disclosed-4-3-2017.pdf (Accessed 03. 01. 19).

MEFCC. (2017b). Federal Democratic Republic of Ethiopia; Ministry of Environment, Forest and Climate Change; Proposal for REDD+ investment in Ethiopia. http://www.mofed.gov.et/documents/10182/32227/REDD%2B+Investment++Plan_program+document.pdf/c39b22eb-abfc-48be-907c-b44ff4505e55(Accessed 03. 02. 18).

Mekonnen, A., Gebreegziabher, Z., Kassie, M., Köln, G. (2009). Income Alone Doesn't Determine Adoption and Choice of Fuel Types: Evidence from Households in Tigrai and Major Cities in Ethiopia. Environment for Development Discussion Paper Series, No. 08-18. Addis Ababa.

Moher, D., Alessandro, L., Tetzlaff, J., Altman, D.G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med, 6:7.

Mondal, A.H., Bryan, E., Ringler, C., Mekonnen, D., Rosegrant, M. (2018). Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. Energy, 149:161-172.

MoWIE. (2014). Federal Democratic Republic of Ethiopia; Ministry of Water, Irrigation and Energy (MoWIE). National Biomass Energy Strategy for Ethiopia. Addis Ababa. http://www.euei-pdf.org/sites/default/files/field_publication_file/Ethiopia_Biomass_Energy_Strategy_and_Action_Plan_Final_2014_02_06.pdf (Accessed 13.06. 18).

MoWIE. (2013). Updated Rapid Assessment Gap Analysis on Sustainable Energy for All (SEforALL). Ministry of Water Irrigation and Electricity (MoWIE), Ethiopia. https://www.se4all-frica.org/fileadmin/uploads/se4all/Documents/Country_RAGAs/MWH_-_Updated-Rapid_Gap_Analysis.pdf (Accessed 12.01.19).

Muller, C., Yan, H. (2018). Household fuel use in developing countries: Review of theory and evidence. Energy Economics, 70: 429-439.

Mulugeta, B., Demissie, S.W., Nega, D.T. (2017). Design, Optimization and CFD Simulation of Improved Biogas Burner for 'Injera' Baking in Ethiopia. Int J. of Engineering Research & Technology, 6(1).

Murphy, J.T. (2001). Making the energy transition in rural East Africa: is leapfrogging an alternative? Technological Forecasting & Social Change, 68 (2): 173-193.

Mwampamba, T.H. (2007). Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. Energy Policy. 35, 4221-34.

Nansairo, A., Patanothai, A., Rambo, A.T., Simaraks, S. (2011). Climbing the Energy Ladder or Diversifying Energy Sources? The Continuing Importance of Household Use of Biomass Energy in Urbanizing Communities in Northeast Thailand. Biomass and Energy, 35 (10): 4180-4188.

Naraina, U., Gupta, S., van 't Veld, K. (2008). Poverty and resource dependence in rural India. Ecological Economics, 66 (4): 161 – 176.

Ndegwa, G.M., ..., Anhuf, D. (2016). Charcoal production through selective logging leads to degradation of dry woodlands: a case study from Mutomo District, Kenya. J Arid Land, 8: 618–31.

Nelson, V.C., Starcher, K.L. (2015). Introduction to Renewable Energy 2nd Ed. CRC Press.

Nepal, R. (2012). Roles and potentials of renewable energy in less developed economies: The case of Nepal. Renew and Sust Ene. Rev., 16:4, 2200 - 2206.

Nkonya, E., Mirzabaev, A., Von Braun, J. (2015). Economics of land degradation and improvement: a global assessment for sustainable development, Springer.

Obiri, B.D., ..., Marfo, E. (2014). The Charcoal Industry in Ghana: An Alternative Livelihood Option for Displaced Illegal Chainsaw Lumber Producers. Tropenbos International, Wageningen, The Netherlands.

Owusu, P.A., Asumadu-Sarkodie, S., Dubey, S. (Ed.). (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. J of Cogent Engineering, 3(1).

Panwar, N., Kaushik, S., Kothari, S. (2011). Role of renewable energy sources in environmental protection. Renew Sustain Ener Reviews, *15*: 1513– 1524.

Phelps, J., Fries, D.A., Webb, E.L. (2012). Win-win REDD+ approaches belie carbon-biodiversity trade-offs. Biological Conservation, 154: 53-60.

Pundo, M.O., Fraser, G.C.G. (2006). Multinomial logit analysis of household cooking fuel choice in rural Kenya: The case of Kisumu district. Agrekon, 45(1): 24-37.

Rahut, D.B., Das, S., De Groote, H., Behera, B. (2014). Determinants of household energy use in Bhutan. Energy, 69: 661–672.

Sathaye, J., ..., Schlaepfer, A. (2011). Renewable Energy in the Context of Sustainable Development. IPCC special report on renewable energy sources and climate change mitigation. Cambridge University Press.

Schlag, N., Zuzarte, F. (2008). Market barriers to clean cooking fuels in sub-Saharan Africa: A Review of literature. Working paper, SEI, Stockholm.

Schwarz, D. (2007). Biogas Technology. Deutsche Gesellschaft für Internationale Zusammenarbeit (GTZ), Eschborn, Germany. https://energypedia.info/images/2/2e/Biogas_Technology.pdf (Accessed 1.1.19)

Singh, N., Nyuur, r., Richmond, B. (2019). Renewable Energy Development as a Driver of Economic Growth: Evidence from Multivariate Panel Data Analysis. Sustainability, 11: 2418.

Tucho, G.T., Weesie, P.D.M., Nonhebel, S. (2014). Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. Renew and Sustain Energy Reviews, 40: 422–431.

Ulsrud, K. (2020). Access to electricity for all and the role of decentralized solar power in sub-Saharan Africa. Norwegian Journal of Geography, 74(1).

Ulsrud, K., Muchunku, C., Palit, D., Kirubi, G. (2018). Solar Energy, Mini-grids and Sustainable Electricity Access: Practical Experiences, Lessons and Solutions from Senegal. Routledge Focus.

UNDP Ethiopia. (2011. Framework for UNDP Ethiopia's Climate Change, Environment, and Disaster Risk Management Portfolio. https://www.et.undp.org/content/ethiopia/en/home/library/environment_energy/publication_1.html (Accessed 12. 05. 19).

United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly. No: A/RES/70/1. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (Accessed 23.03.18)

Valentine, S.V. (2011). Emerging symbiosis: Renewable energy and energy security. Renewable and Sustainable Energy Reviews,15: 4572– 4578

van der Kroon, B., Brouwer, R., Beukering, P.J.H. (2013). The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. Renewable and Sustainable Energy Reviews, 20: 504 – 513

Wamukonya, N., Davis, M. (2001). Socio-economic impacts of rural electrification in Namibia: comparisons between grid, solar and unelectrified households. Energy for Sustainable Development, 5(3):5-13.

World Bank. (2019). The World Bank in Ethiopia: Overview. https://www.worldbank.org/en/country/ethiopia/overview (Accessed 2. 3 .19)

World Bank. (2018). Population Total- Ethiopia, data for 2018. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=SL-ET (Accessed 29.06.19)

World Bank. (2017). Sustainable Energy for All (SE4ALL): Access to electricity, rural (% of rural population) Ethiopia in 2017. https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS (Accessed 21.03.19)

Yurnaidi, Z., Kim, S. (2018). Reducing Biomass Utilization in the Ethiopia Energy System: A National Modelling Analysis. Energies, 11(7): 1745.

Zeleke, B., Getachew, M. (2017). Traditional Cattle Husbandry Practice in Gamo Gofa Zone, Southern Western Ethiopia. Int. Journal of Novel Research in Life Sciences, 4(5): 1-7.

Paper I

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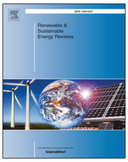

Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence

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ABSTRACT

This paper aims to provide a comprehensive review and analysis of the potential impacts of Small-scale Renewable Energy Technologies (SRETs) in reducing deforestation, forest degradation and carbon emissions in the Eastern African region. A systematic review approach was used to select, critically analyze and synthesize findings of various studies in the region. The review showed that SRETs, if efficiently and uninterruptedly used, could significantly reduce household consumptions of traditional biomass and fossil fuels, and hence, can reduce deforestation, forest degradation and carbon emissions from biomass energy use at household levels. The FAO charcoal to dry wood conversion rate and the IPCC conversion factor of fuelwood from dry weight to CO_2 equivalent were used to estimate potential wood fuel and CO_2e emissions savings. Our conservative estimates based on the analysis of the evidence indicated that domestic biogas and improved cook stoves distributed up to now have a combined potential of saving 0.307–3.100 million tons of wood fuel and 0.562–5.673 million tons of CO_2e emissions per country per year. However, when compared to the annual biomass energy consumptions of each country, the potential wood fuel savings from the biogas plants and improved cooks-stoves disseminated so far do not appear to offset more than 7.2% of the national demands of the respective countries. The review suggests that building on the household level positive results for scale and lasting impact at national and regional levels requires addressing key policy, technical, financial and sectoral integration barriers.

1. Introduction

East Africa otherwise known as Eastern Africa is part of the sub-Saharan Africa encompassing the easternmost region of the African continent (Fig. 1). According to the African Development Bank [1], the east African region consists of 13 states: Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Rwanda, Seychelles, Somalia, South Sudan, Sudan, Tanzania and Uganda. In 2016, the population in the region was estimated at 342 million people, roughly a third of the population of the entire continent [2]. East Africa is endowed with a wide variety of renewable energy resources: from biomass, hydropower to solar, geothermal and wind [3]. If properly developed and efficiently utilized these energy resources, widely distributed throughout the region, could play pivotal role for the sustainable development of the people and the countries in the region.

However, the energy sector throughout the region remains largely undeveloped with extremely low rate of access to modern and clean energy sources [4]. Evidently, more than 80% of the population in East Africa have no access to electricity [4]. While there are many positive efforts and encouraging recent developments in providing access to electricity, modern energy supply has not yet kept pace with the rising energy demand and rapid population growth in the region. For instance, the four most populous countries in the region; Ethiopia, Kenya, Tanzania, and Uganda had in 2014 a total net installed electricity generating capacity of only 2311, 2094, 1115, and 883 Megawatts (MW) respectively [5]. In particular, in rural areas of the region where roughly 80% of the population lives [6], the rate of access to electricity is on average less than 7% [7]. As a result, traditional biomass fuels mainly fuelwood, charcoal, animal dung and crop residues dominate the energy sector of countries in the region accounting for more than 90% of the total primary energy consumption of the population [8–10].

This heavy dependence on traditional biomass fuels has in turn led to overexploitation of forests and woodland resources, thus accelerating the deforestation and forest degradation in the region [11–15]. The unsustainable exploitation and inefficient use of traditional wood fuels is also strongly linked to higher greenhouse gases (GHGs) emissions from incomplete combustion of biomass and loss of natural carbon sinks, the forest resources [16]. The dry-forests and woodlands of the

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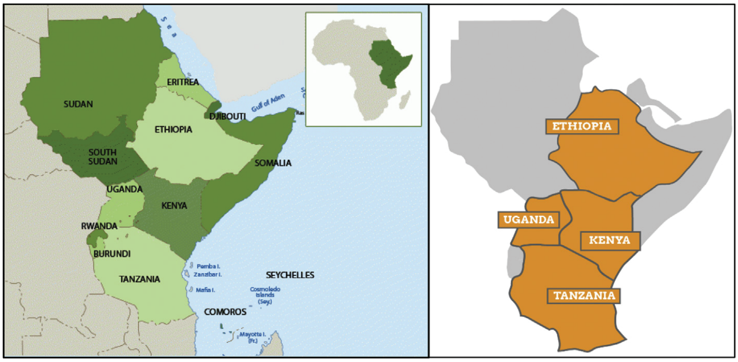

Fig. 1. Map of the east African region and countries selected for the study (Source: AfDB [1]).

region are in particular most impacted for the largest share (≈77%) of the charcoal consumed in the region is derived from these ecosystems [11,15,17], unpublished] [18–20]. For instance, a comprehensive review by Felix and Gheewala [21] showed that in 2002 alone, charcoal production has resulted in the degradation of 29,268 ha of closed woodlands and deforestation of 116,069 ha of closed and open woodlands in Tanzania only to meet the charcoal demand of Dar es Salaam city (the capital of Tanzania). Traditional biomass energy use is also associated with severe indoor air pollution and chronic health problems especially for women and children [22]. According to the WHO [23] in Ethiopia alone indoor air pollution from biomass-fuel burning is responsible for the death of 72, 400 people every year.

To address the rapidly growing energy demand amid intensifying environmental degradation, many countries in the region have been actively pursuing the development and deployment of alternative renewable energy sources and energy-efficient technologies over the last two decades. The goal is to achieve energy security and sustainable energy development through diversifying national and local energy generation portfolios towards a steady transition to clean and renewable sources. However, as strongly argued by Lior [24] even for developing regions like Africa in which there is a pressing need for energy security, energy development utterly needs careful planning and execution, with sustainability imperatives to reduce the associated disastrous environmental and social impact. To this end, national governmental energy agencies with the technical assistance from international organizations, primarily the German Technical Cooperation Agency (GIZ) and the Netherland Development Organization (SNV), have been disseminating various small-scale renewable energy technologies (SRETs) to increasing number of households and small businesses in the region. The main SRETs disseminated hitherto are domestic biogas plants, improved biomass cook stoves (ICS) and solar photovoltaic (PV) home systems (SHS).

In this regard, reports mostly produced by the organizations and agencies promoting the SRETs and a number of scholarly evidences claims that the adoption of the SRETs is yielding substantial socio-economic and environmental benefits at local, national and regional levels [25–28]. For example, a report by the National Biogas Programme of Ethiopia [28] claims that one biogas plant can prevent the deforestation of 0.3 ha of forest per year by reducing household fuelwood consumption. This reduction in fuelwood consumption corresponds to mitigation of 4 tons of CO_2e per biogas plant per year.

Likewise, several published studies [30–37] have also indicated that efficient use of biogas plants and ICS can significantly reduce dependence of households on traditional biomass fuels and fossil fuels for domestic energy. A study by Dresen et al. [29] in rural Ethiopia showed that households who adopted ICS were able to reduce their fuelwood consumption for cooking by nearly 40% compared to households using the traditional open-fire stoves. This equates to an annual saving of 1.28 tons of fuelwood per household per year. In addition, a study by Ghimire [37] on biogas plants installed by SNV in Asia and East Africa found that one fixed-dome biogas plant could reduce the fuelwood consumption of a biogas-user household by 3.65 tons per year. Given the increasing pressure to meet the energy demand of a growing population and economy in the region, these studies have spurred great optimism that east Africa countries could potentially leapfrog the current energy-environment crisis by effectively utilizing renewable energy sources and technologies.

By contrast, other studies have shown differing views largely downplaying the magnitude of impact of SRETs in inducing rapid energy transition, sustainable forest management, and climate change mitigation [30,38]. For instance, a recent study by Berhe et al. [39] in Ethiopia revealed that the majority of households who adopted domestic biogas technology were still predominantly dependent on traditional biomass fuels. According to the study, availability of the biogas technology has rather increased the household energy consumption while producing negligible or no effect in reducing or replacing the traditional fuels. Similar studies by Lusambo [40], Guta [41], and Mekonnen and Köhlin [42] found that households in rural Africa are adopting a ‘multiple-fuels use’ strategy contrary to the ‘energy-ladder’ hypothesis of shifting from traditional biomass to modern and clean energy sources as their income and –access to renewables-increases. Karekezi and Kithyoma [43] argued that despite the concerted efforts in the promotion of solar PV, majority of rural households in Africa would continue to depend on traditional biomass fuels.

Notwithstanding the differing views, an important question that needs to be thoroughly addressed is how large and significant is the impact of these SRETs in reducing deforestation and CO2e emissions in the broader scale at national and regional levels, apart the household level contributions. In this regard, most of the published papers were narrow in their scope drawn from household level and specific case studies from a district or two within a country. Essentially, the papers fall short of providing a comprehensive assessment and contextual analysis of the overall significance and synergy of SRETs in combating deforestation and climate change at national and regional levels. This present paper aims to provide a comprehensive review and critical analysis of the empirical and qualitative evidence on the impacts and implications of use of SRETs for sustainable forest management and climate change mitigation at local, national and regional level in East Africa. The review draws data and experience from a wide range of scientific studies and gray literature from four most populous countries in the region: Ethiopia, Kenya, Tanzania and Uganda. The paper employs a systematic review approach integrating empirical analysis with qualitative synthesis. Doing so, the paper attempts to assist policy makers, researchers and practitioners in the region exploit existing knowledge, identify critical gaps, and position future research and development works for the deployment of environmentally and economically sound SRETs.

2. Material and methods

2.1. A systematic review

A systematic review is a rigorous review of all high quality and relevant existing literature (both published and gray literature) to address pre-formulated research questions [44]. It uses explicit and reproducible methods to systematically identify, select, evaluate and synthesize all relevant original scientific studies and gray literature pertinent to the specified research questions [45,46]. A good systematic review entails the formulation of a comprehensive and explicit review protocol with a sound literature searching strategy and clearly defined eligibility criteria for inclusion and exclusion of candidate studies [45]. Eligible studies and literature are then subjected to subsequent screening and objective evaluation for relevance and quality. Accordingly, in this review, we have employed the guidelines and formats proposed by Bowler et al. [45] and Moher et al. [47].

2.2. Key research questions of the paper

The main research questions addressed in this review are:

- RQ1. What is the trend of adoption and use of SRETs in East Africa?
- RQ2. Are users of SRETs consuming less biomass and fossil fuels than before/non-adopters?
- RQ3. How significant is the impact of SRETs in reducing CO_2e emissions of households
- RQ4. Are SRETs leading to household energy transition towards clean and renewable sources in East Africa?
- RQ5. How significant is the impact SRETs in reducing deforestation and forest degradation at national and regional levels?
- RQ6. How significant is the impact of use of SRETs in reducing CO_2e emissions and mitigating climate change at national and regional levels?
- RQ7. What are the major barriers and setbacks hindering the diffusion and efficient use of SRETs in the region?

2.3. Inclusion and exclusion criteria

This review specifically focuses on scientific and gray literature on three SRETs namely; biogas plants, SHS and ICS that are being widely distributed to rural and urban households, small-to-medium enterprises (SMEs) and institutions both for domestic and commercial purposes in East Africa. Much of the data and information is drawn from studies and reports in East Africa. For that purpose, five criteria were developed to identify, screen and select relevant scientific studies and gray literature for inclusion and exclusion from the review.

- **Subject relevance:** studies that primarily dealt with environmental impacts of SRETs, biomass and fossil fuels consumption, energy substitution, impact on deforestation and land degradation, carbon emission and climate change mitigation were largely eligible for inclusion.
- **Type of technology**: studies that primarily dealt with use of biogas plants, SHS (including solar cookers), and ICSs were foremost eligible for inclusion.
- **Geographic scope:** studies conducted in East Africa mainly in Ethiopia, Kenya, Tanzania and Uganda were eligible for inclusion. However, few studies in other developing regions were also included when such studies have unique and relevant evidence related to the context in East Africa.
- **Intervention scale:** Studies that primarily focused on small-scale use of renewable technologies by households, SMEs and public institutions for all purposes were eligible for inclusion.
- **Type of data:** Both quantitative and qualitative studies were considered for inclusion; studies with sound empirical analysis were particularly preferred.

2.4. Search strategy and data sources

Searching for relevant studies and gray literature was conducted by using databases of scientific journal publishers, internet search engines, and websites of different academic and development organizations. For it is imperative that the search is sufficiently broad yet specific enough to cater all the high-quality relevant studies and literature, a comprehensive and structured search strategy combining key terms and phrases was used as summarized hereunder.

2.4.1. Journal articles

Published scientific papers were searched and accessed between 07 March and 05 August (2017) through the Norwegian University of Life Sciences (NMBU) links to databases and websites of e-journals. The main e-journal publishers and links accessed were Science Direct, Springer, Elsevier, and ResearchGate. The keywords and phrases included in the search algorithm were: a**) biomass fuels** ("traditional biomass," "wood-fuel," "charcoal," "fuelwood," "firewood," "fuel wood,"; **b) deforestation and forest degradation** ("deforestation," "forest degradation," "environmental impact" "GHGs emission," "CO_2e emission"; **c) renewable energy technologies** ("renewable energy," "biogas," "solar photovoltaics," "solar home systems," "solar cookers," "improved cook stoves," "adoption," "dissemination," "use," **d) utilization** ("household," "rural," "urban," "domestic"; "institutions," "micro-enterprises," "East-Africa," "Kenya," "Ethiopia," "Tanzania," "Uganda," **e) environmental impacts** ("biomass-conservation" "fuelwood saved" "charcoal saved" "environmental benefits" "GHGs/CO_2 emissions reduction," "biodiversity conservation," "climate change mitigation" "sustainable forest management").

2.4.2. Unpublished studies and gray literature

Search for relevant unpublished and gray literature was conducted by using websites and databases of local and international research and academic institutions, NGOs, government ministries and international energy agencies. The keywords used in the search were adapted from the preceding search strategy to fit to the information sought from the different organizations.

2.5. Identification and selection of studies

Following the comprehensive literature search, 659 potentially eligible records were identified and retrieved. First stage screening for duplication and unrelated at title led to the exclusion of 344 records. In the second stage, the abstracts and executive summaries of the remaining 315 records were read and evaluated based on the inclusion and exclusion criteria. As a result, 184 of the 315 records were excluded after reading the abstracts mainly because they did not meet the inclusion criteria. Subsequently, full-text evaluation was conducted for the remaining 131 records, of which 43 more were excluded on the grounds of limited relevance, poor quality and unreliability of data. Finally, 88 studies (47 quantitative and 41 qualitative) were selected for the systematic review. The flow diagram for the searching and extracting of data is presented in Fig. 2.

2.6. Research quality assessment and data extraction

Both objective and subjective evaluation criteria were used to assess and determine the quality of the studies and reports to be eligible for inclusion. The evaluation criteria included; the theoretical basis and relevance of the research; research methodology and design; reliability

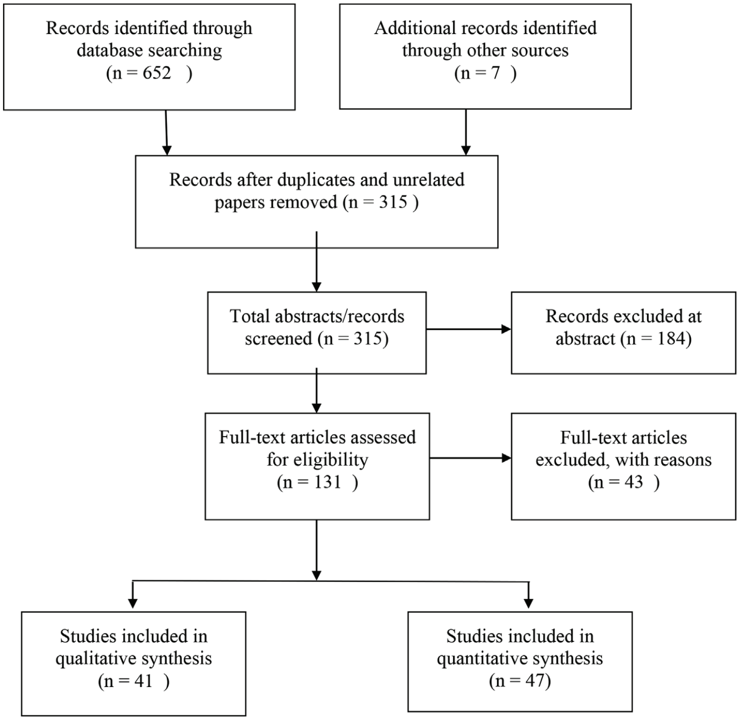

Fig. 2. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) flow diagram for searching and extracting data (adapted from Moher et al. [47]).

of data sources; and quality of the analysis. Both quantitative and qualitative information related to the research questions were systematically extracted. An integrated empirical analysis and qualitative synthesis approach was used to interpret and critically analyze the findings and implications of the studies.

3. Results and discussion

3.1. Traditional biomass fuels and deforestation in East Africa: an overview

Traditional biomass fuels, mostly fuelwood and charcoal, are the major sources of primary energy for sub-Saharan Africa accounting for 76–80% of the total energy supply mix [48,49]. The share of traditional wood fuels is even much higher in the energy supply-mix of the East African region particularly in the household sector [50]. The household sector represents the largest category in biomass energy consumption in the region, and cooking comprises almost all of the energy demand in the household sector. In Kenya for instance, Ndegwa et al. [11] reported that more than 90% of rural and more than 80% of urban households rely on fuelwood and charcoal as primary sources of energy for cooking and heating. In Uganda, over 90% of the population depends on charcoal and fuelwood as primary sources of energy for cooking [51]. Uganda's Ministry of energy and mineral development [52] reported that fuelwood and charcoal combined constituted most of the fuel consumed by 96% of households in the country.

Likewise, Ethiopia's energy sector is highly dependent on biomass fuels. In 2001, it was estimated that biomass fuels accounted for 93% of Ethiopia's total energy consumption [50]. More recently, IEA reported that nearly all rural households and 80% of urban households in Ethiopia depend on solid biomass for cooking [4]. In Tanzania, traditional wood-fuels dominate the national energy balance accounting for about 90% of the total energy consumption in the country [21,40]. Besides the household sector, fuelwood and charcoal are also vital energy sources for small-medium scale enterprises, cottage industries, restaurants and learning institutions in the region [53].

However, the heavy dependence and unsustainable exploitation of traditional biomass fuels has not come without sever strain to the forest and environmental resources of the region. Studies have shown that the over-reliance on traditional wood fuels coupled with inefficient energy production and use has been driving the deforestation and environmental degradation in the region. Biomass is a renewable energy resource per se and small-scale household fuelwood collection has been argued to have little impact on deforestation [54,55]. Notwithstanding, several studies have contested this and have shown that unsustainable exploitation of forests for fuelwood (including commercial firewood), and selective logging and clearcutting for commercial charcoal production has led to the disappearance of large patches of forest in the region and throughout sub-Saharan Africa [11,20,53,56]. According to Subedi et al. [57], about 70 (± 42) % of the deforestation observed in Africa in 2010 was attributed to demand for wood-fuel.

A comprehensive study by Ethiopia's REDD+ secretariat [58] reported that the main drivers of deforestation and forest degradation in all regions of the country are free livestock grazing, fodder use, and fuelwood collection and charcoal production followed by farmland expansion, fire and wood harvesting for construction. Another extensive review by Felix and Gheewala [21] indicated that following the rapid population growth in Tanzania, consumption of wood-fuels has climbed drastically resulting in widespread deforestation and shortage of biomass resources in the country. Uganda's Ministry of Energy and Minerals Development [52], reported that charcoal and fuel-wood stand as the second foremost drivers for the 2% annual loss of forest cover in the country after land-clearing for agriculture.

The burden from the overreliance on biomass fuels is most prominent on dry forests and woodlands of East Africa for these ecosystems are especially targeted for commercial fuelwood and charcoal production due to their high quality hardwood species [18,52]. Evidently, most of the charcoal produced and consumed in the region and even smuggled to the Middle East comes from dry forests and woodlands [11,17]- unpublished] [18,59]. In Kenya for instance, Kirubi et al. [19] found that the rate of deforestation in the dry forests and woodlands of Marsabit district (Northern Kenya) was 1.6 ha per year compared to the national average 0.34 ha per year in 2000. The main reason for the high rate of deforestation in Marsabit, according to the authors, was commercial charcoal production from the woodlands. The impacts, they concluded, were disappearance of valuable indigenous tree species such as *Olea* spp. and *Teclea* spp, destruction of fragile ecosystems and substantial loss of biodiversity.

Felix and Gheewala [21] reported that almost all the charcoal supply to major towns in Tanzania came from woodlands and dry forests. Similarly, a study by Gebreegziabher et al. [13] in Tigray region of Northern Ethiopia showed that urban households meet 85% of their energy needs from wood fuel supplied by rural households harvested from dry forests and woodlands in adjacent districts. In the same line, a national survey of charcoal production and value chain in Ethiopia by Bekele et al. [17]-unpublished] found that of the estimated 2.98 million tons of charcoal produced per year in the country; more than 77% came from 'open access' exploitation of dry forests and woodlands in the country.

A major player in the steeping negative environmental impacts of traditional biomass energy use are also the inefficient energy production and use technologies such as the traditional charcoaling kilns and cooking devices. Okello et al. [51] estimated that the efficiency of traditional biomass-cooking stoves used by 72.7% of the population in Uganda is less than 10%. As a result, the high level of wastage of biomass from the inefficient cooking devices has accelerated the rate of deforestation and degradation of soil and biodiversity resources of the country.

Similar studies have shown that traditional cooking technologies such as the three-stone fire stoves are inefficient resulting in significant loss of wood; and high levels of carbon dioxide (CO_2) and other pollutant emissions leading to severe indoor air pollution and health risks from the smoke coming out of the biomass stoves [22,60,61].

3.2. Adoption and dissemination of SRETs in East Africa

The introduction of renewable energy technologies to East Africa dates back to early 1950s, when a European farmer introduced the first biogas plant to a coffee farm in Kenya [62]. Despite its old age, it was only during the last 20 years that interest for SRETs revived in the region [12,62]. The main reasons for the renewed interest in SRETs could be due to rise in fossil-fuel prices, rapid deforestation and fuelwood-crisis, severe energy scarcity and international support for alternative renewable energy technologies development. In this respect, the most noticeable and sustained efforts made so far in the region are the domestic biogas, ICS and Solar PV dissemination programmes that have been assisted by GIZ, SNV and other non-governmental organizations (NGOs). These programmes are implemented in partnership with local government structures in each country. As a result, growing number of biogas plants, ICS and SHS are being disseminated and installed by rural and urban households, SMEs and public institutions in the region (Table 1).

Table 1
Estimated number of SRETs disseminated in selected countries in the region. Source: (compiled from reports by government ministries, NGOs, and energy agencies)

Country	Biogas plants	Improved Cook-Stoves (ICS)	Solar Home Systems (SHS)	Year
Ethiopia	15,000	3,300,000	40,000	2005–2015
Kenya	17,500	1,300,000	445,000–470,000	2006–2015
Tanzania	12,000	1,200,000	65,000	2006–2014
Uganda	6100	561,000	26,000	2005–2015

3.2.1. Biogas plants

Since 2009, the African Biogas Partnership Program (ABPP) with the technical assistance from SNV has been developing the domestic biogas sector in much of the region. The main types of the biogas plants installed are the fixed dome, floating drum, and inflatable tubular reactor designs; with sizes ranging from 3 to 15 m^3 [63,64]. To date, ABPP in partnership with local biogas implementation structures in the four countries has constructed and installed more than 57,000 biogas plants to households and SMEs [24]. In Kenya, SNV [57] reported that as of 2017, over 17,500 biogas plants have been installed by the ABPP initiative. By the end of 2016, the National Biogas Programme of Ethiopia (NBPE), part of the ABPP, has supported the installation of over 15,000 domestic biogas plants in the country [65]. Fig. 3 shows a bio-digester under construction in Meskan district of Southern Nations, Nationalities, and Peoples' Region, Ethiopia.


Fig. 3. Bio-digester under construction: Meskan District, Southern Ethiopia (SNV [65]).

Similarly, SNV [65] reported that the Tanzania Domestic Biogas Programme (TDBP), part of the ABPP, has supported the installation of 12,000 biogas plants in the country. In contrast, over the same period the Uganda Domestic Biogas Programme (UDBP), part of the ABPP, has installed some 6100 biogas plants in the country. Lwiza et al. [63] explained that the main reason for the exceptionally low number of biogas plants installed in Uganda was due to large dis-adoption of the technology in previous years. According to the study, adoption of domestic biogas in Uganda began as early as the 1990s with majority of households taking up the technology between 2003 and 2009. However, by 2015, more than 29% of the households had dis-adopted the technology. The main reasons were mentioned as inability to sustain cattle and pig production that were necessary for raw material (animal dung) supply, reduced availability of family labor and lack of maintenance of the biogas plants after malfunctioning.

3.2.2. Improved cook-stoves (ICS)

The deployment of energy-saving improved cook-stoves has been one of the priorities of many East African countries to advance efficient use of biomass energy, hence reduce deforestation, improve health conditions of users and minimize GHGs emissions. In this regard, the national improved cook stove program of Ethiopia with the technical assistance from GIZ (and other NGOs) has reportedly produced and disseminated about 7 million improved cook stoves to households and small businesses since 2005 [66]. However, a recent study by Alemayehu [64] has estimated the number of ICS currently in use to be about 3.3 million. The most common types of ICS disseminated include the '*Mirt*' and *'Gonziye'* fuelwood-efficient 'Injera' baking stoves, and '*Lakech'* charcoal-saving cook stove [64]. Kenya has the second highest number of dissemination of ICS with an estimated 1.3 million ICS of different designs taken up by households so far [26]. Among the more popular stoves introduced were the *Kenya Ceramic Jiko* (KCJ) charcoal-saving stove and the *Kuni mbili'* and *'Upesi jiko' fuel*wood-saving stoves [67].

In Tanzania, the use of energy-saving improved cook-stoves has been slow in the past-as was the case in other parts of East Africa. However, over the last few years Tanzania's market for ICS has grown steadily. With an estimated annual production of 500,000, the Tanzanian version of Kenya's KCJ stoves, the *Jiko-Bora* stoves, are most popular especially in urban areas in terms of acceptance and sells volumes [68,69]. By 2014, it was estimated that about 1.2 million households were using ICS in Tanzania [68]. According to the Uganda National Household Survey [70], about 561,000 households were using fuelwood-efficient and charcoal-saving ICS in Uganda by 2010. The survey indicated that the number of households using ICS did not show an overall increase compared to the 2005 survey suggesting a negligible number of new adopters of the technology between the surveys. Similarly, a study by Kees and Feldmann [71] has also reported that with the technical assistance from GIZ an estimated 500,000 ICS had been distributed to rural and peri-urban households of Uganda until 2011.

3.2.3. Solar home systems and solar cookers

With the bulk of the East African population residing in dispersed rural villages, studies have suggested that conventional grid-connected electrification is currently too costly for most countries in the region [10]. The dispersion problem along with the abundant solar radiation makes East Africa an ideal place for the deployment of decentralized and innovative rural solar energy systems that are cost effective and environmentally sound [74]. In this regard, Dekker et al. [75] note that rural electrification by using hybrid power generation systems integrating two or more types of energy (renewable) sources and storage devices-depending on the climatic zone-can be seen as a cost effective solution in contrast to extending the utility grid in remote areas of poorer countries. Though, the development and utilization of small-scale solar energy systems had been generally low in East Africa [74–76], the use of solar PV systems is increasing, especially in rural east Africa. According to Hansen et al. [77], two emerging trends are developing in the solar energy sector of East Africa. The first is a move from donor - supported programmes to market-driven diffusion of technologies. The second is a steady transition from off-grid, small-scale decentralized solar PVs to mini-grids and large-scale, grid-connected solar power plants.

One of the key factors driving the increase in diffusion of SHS in the region are attributed to the decline in market prices of PV modules; coupled with strong support from government incentives and international donors [24]. Kenya has by far the most vibrant solar energy adoption rates in East Africa with strong presence of the private sector, particularly in the small-scale PV markets [80]. According to Ondraczek [80], in 2010 an estimated 320,000 rural households (4.4% of the rural population) in Kenya have SHS. With an estimated 25,000 to 30,000 PV products annually sold in the Kenyan solar market, KCIC [81] and IREK [82] estimated that between 445, 000 to 470,000 PV systems totaling more than 60 MW have been installed in Kenya as of 2015 assuming each household has only one PV system. According to the Solar Energy Foundation, as of 2016, about 40,000 SHS have been distributed to rural households, SMEs and institutionsin Ethiopia [83].

Akin to the situation in Ethiopia, the dissemination of SHS in Tanzania and Uganda is slowly improving over the years. According to Ondraczek [80], in 2008, rural households in Tanzania were using about 40,000 SHS systems with an estimated installed capacity of 4 MWp. With an estimated annual sales of 4000 to 8000 SHS, about 65,000 houses are currently using solar PV panels in Tanzania with a capacity ranging from 10 to 100 W per house [84]. In Uganda, the rate of dissemination of small-scale solar PV technologies is growing since 2007 with almost exclusively served by the private sector. According to IEA [4], IRENA [85] and GIZ [28], an estimated 26,000 SHSs have been installed between 2007 and 2015.

Compared to the solar PV systems, the adoption and use of solar cookers in East Africa is at its embryonic stage [43,86]. Despite relentless efforts from international NGOs, local governments and private businesses, the adoption and diffusion of solar cookers has been disappointingly limited [43,86]. According to Kebede and Mitsufuji [87], the major barriers behind the sluggish rate of adoption of solar cookers in East Africa is the lack of integration among solar actors and the financial problem facing both sides of the supply chain. Tesfay et al. [88] explained that another important reason for the slow adoption of solar cookers in Ethiopia is because the systems can only be used outdoor and at time of sun shine. Nevertheless, solar cooking is slowly getting its foot in Kenya and Tanzania, particularly in drier regions where fuel wood resources are largely depleted. Even so, there is very little reliable and organized data available on the current status of adoption and use of solar cookers in these countries and the region at large. Fig. 5 shows different types of solar cooker in Uganda and solar photovoltaic powered water pumping system in Tanzania.

3.3. Impact in reducing wood-fuel consumption and CO_2 emissions at local levels

3.3.1. Biogas plants

One of the fundamental motivations for the deployment of SRETs in East Africa has been the firm ground that adoption and use of these technologies would help reduce and substitute the consumption of traditional biomass fuels thereby, alleviating the pressure on forest resources. On this premise, studies have shown that utilization of small-scale biogas plants is strongly linked to significant reduction in consumption of wood-fuels at household and local levels. For instance, a study carried out in Fogera district of Northern Ethiopia by Amare [31] found that after the installation of biogas plants, the average fuelwood consumption of an average household declined from 3596 kg to 1062 kg per year; i.e. a reduction by 70% of fuelwood per household per year. In terms of charcoal, the study showed that before the biogas installation an average household in the study area consumed 324 kg of charcoal per year but after installation of the biogas plants all biogas user households have abandoned the use of charcoal. The same study found that before the installation of biogas, an average household used between 138 kg and 230 kg of animal-dung cakes as cooking fuel; but after the biogas installation, the majority of biogas user households consumed between 11.5 and 46 kg of animal-dung, i.e. a reduction by 80–92%.

In a study conducted in rural Ethiopia, Tajebe [32] estimated that the 10,678 biogas plants disseminated in the country between 2008 and 2014 saved about 8732 tonnes of charcoal and 27,162 tonnes of fuelwood. According to the author, the total fuel replaced by clean energy from the biogas plants was equivalent to 66,463 tonnes of biomass and 485 tonnes of fossil fuel. Decomposing the aggregate figures to individual plants shows that, on average a biogas user household consumes 818 kg less charcoal per year and 2544 kg less fuelwood per year because of the biogas use.

Translating the effects, the author estimated that the 10,678 biogas plants disseminated in the country by the time could reduce the emission of 64,684 tonnes of CO_2e per year in the country. Similarly, Mengistu et al. [33] showed that substituting traditional biomass fuels and kerosene with biogas energy enabled biogas-user households in rural Ethiopia to reduce, on average, 1.9 tonnes of CO_2e per plant per year. This implies that a biogas owner household on average saves about 1,038 kg of fuelwood per year. Given the frequent droughts and climate-related risks Ethiopia is facing, these findings suggest that biogas plants can lessen the extreme dependence on forests for fuel thereby contribute to the country's GHGs emission reduction and climate change adaptation efforts.

In accord with the findings in Ethiopia, a study by Laramee and Davis [34], in Tanzania found that an average biogas user household consumes 5376 kg less firewood and 48 L less kerosene per year compared to non-users who mainly rely on charcoal and liquefied petroleum gas(LPG). According to their findings, the reduction in wood-fuel consumption due to the biogas amounts to an average emissions reduction of 5825 kg CO_2e per household per year. The study also indicated that most households (75% of adopters and 80% of non-adopters) use more than one type of cooking fuel with only 25% of biogas adopters reporting of using exclusively biogas for cooking. A study by the Institute of Resource Assessment, the University of Dar es Salaam, in 2005 showed that following the adoption of a biogas plant the firewood consumption for Lomwe Secondary School decreased from 700 to 145 m^3 [84]. The study estimated that the annual fuelwood saving from implementing the biogas plant was equivalent to a reduction from 253.9 to 53.8 tonnes of CO_2e per year (79% reduction). The institute concluded that as a result of the biogas project the school has been able to considerably reduce deforestation at local level and preserve the forests and the ecosystem services it provide [35].

A study in Uleppi sub-county of Uganda by Menya et al. [36] showed that households with a biogas plant with an average production capacity of 0.48 m^3 per day were able to reduce wood-fuel consumption from 6.65 kg per day to 2.24 kg per day per household. This is about 4.41 kg less fuelwood per household per day, equivalent to 1610 kg of less fuelwood per household per year. Projecting the results, they estimated that if all the 1459 households in the sub-county use biogas technology, 2349 tonnes of wood fuel (i.e. 66.3% reduction) would be saved per year. This implies that if all the households in Uleppi sub-county adopt the biogas technology, 432 tonnes of CO_2e emissions would be avoided per year. A more generalized assessment of the fuelwood-saving impact of fixed-dome biogas plants sizing from 4 m^3 to 15 m^3 was made by Ghimire [86]. Based on his assessment for the 300,000 biogas plants installed by SNV both in Asia and Africa by 2013, the author estimated that more than 600,000 m^3 of biogas was produced each day, thus substituting the harvesting of more than 3000 tonnes of fuel wood. This means, one fixed-dome biogas plant installed by SNV in Kenya or Uganda has the potential to reduce the fuelwood consumption of a biogas-user household by about 3650 kg per year.

The above results demonstrate that small-scale domestic biogas technology if efficiently used can significantly reduce household consumption of traditional biomass and fossil fuels for cooking. These evidences also suggest that adoption of biogas technology has partially triggered household energy transition from wood fuel-based to renewable and cleaner sources. This is in alignment with the 'energy ladder' hypothesis [89]; of a five-rung transition from fuel wood to electricity as household income, thus access to renewable energy, increases. Nevertheless, the findings also reveal that households who adopted the biogas technology did not completely abandon the use of fuelwood and animal-dungs.

For instance, Amare [31] in Ethiopia showed that rural households rather limited their use of fuelwood mainly to baking 'Injera'-Ethiopia's staple bread, and animal-dung to other cooking activities as opposed to completely shifting to biogas energy. Similarly, Laramee and Davis [34] also found that apart from biogas, both adopters and non-adopters of the biogas technology were using firewood as their primary cooking fuel.

The reluctance of households to completely abandon traditional fuels such as fuelwood despite increased access to renewable sources in part concurs to the 'fuel-stacking' hypothesis [90] of using multiple cooking fuels by households to ensure energy security. Another reason could be the unsuitability of the biogas appliances to local cooking cultures and preferences as observed in the arrangement of the '*Injera*' baking stove in Ethiopia (Fig. 4).

The results imply that the relationship between availability of renewable energy and energy transition among rural households of East Africa is not linear and unidirectional as previously assumed; nor do rural households strictly stick to the multiple fuels as evidenced by the total abandonment of charcoal in Amare [31] study. Regardless, the findings validate that efficient use of biogas technology can play pivotal role in reducing the heavy dependence on wood-fuels thus minimizing deforestation, environmental degradation and GHGs emissions from unsustainable use of traditional biomass and fossil fuels. Overall, the above findings generally accord to the claims of SNV and national biogas programs in the four countries.

3.3.2. Improved cook-stoves

Several empirical studies reviewed in this paper show that substitution of traditional inefficient cook stoves with ICS can lead to considerable biomass conservation, and hence reduced forest degradation, indoor air pollution and associated health problems. Findings of Adkins et al. [91] showed that compared to the traditional three-stone stoves the performance of ICS in East Africa ranged from 22 to 46% in terms fuelwood saved per household per year. However, the results vary depending on several factors including the type and design of the stove, type of food cooked, cooking time and stove size [91,92].

A review by MacCarty et al. [93] on the performance of different ICS in sub-Saharan Africa found that, on average, the fuel use of an ICS was 33% less and CO_2e emissions 75% less in comparison to the traditional three-stone open-fire stoves. Findings from Gebreegziabher et al. [94] showed that an average household in Tigray region of Northern Ethiopia using an ICS collects about 70 kg less fuelwood and 20 kg less animal-dung each month. This amounts to an average fuelwood saving of 840 kg per household per year. For historically overexploited and degraded forest resources of the area, the results imply a considerable positive impact in slowing degradation of forests and woodlands, and improving agricultural productivity from less collection of animal dung for energy purposes and thereby, available to be used as fertilizer.

Similarly, using a randomized experimental design and controlled cooking tests, Beyene et al. [95] estimated the fuelwood and carbon emissions savings from improved cook stoves that were being implemented in rural Ethiopia in 2015. According to their findings, on average one ICS saves about 634 kg of fuelwood per year that translates to about 0.94 tonnes of carbon equivalent per year.

A study by Dresen et al. [30] in Kaffa region of southern Ethiopia showed that when used efficiently ICS can significantly reduce the pressure on forest resources from demand for fuelwood while also contributing to mitigation of climate change. Taking the 11,000 ICS locally known as "*Mirt*" stoves distributed specifically for baking '*Injera*', the authors found nearly 40% fuelwood savings in *injera* preparation compared to the traditional three-stone fire. According to the study, the reductions in fuelwood consumption amounts to a total annual savings of 1.28 tonnes of fuelwood per household, equivalent to 11,800 tonnes of CO_2e emission savings from the 11,156 ICS disseminated in the district.

In Kenya, Helga [96] compared the performance of improved charcoal-saving *KCJ-Jiko* stove, and the fuelwood-burning *Kuni mbili'* and *'Maendeleo jiko* stoves with traditional three-stone fire stoves. The results showed that use of the fuelwood and charcoal-saving ICS saves up to 30% of the wood needed for cooking. A study by Coelho et al. [97] in Kenya revealed that following the adoption of *KCJ*-stoves the consumption of charcoal among households on average fell from 0.67 kg to 0.39 kg per day, equivalent to saving over 600 kg of charcoal per year per household. Likewise, UNFCC estimated that the average annual fuelwood saved from one biomass energy-efficient cook stove in Kisumu county of Kenya was about 1350 kg per stove per year [98].

In Tanzania, the Tanzania Traditional Energy Development Organization(TaTEDO) reported that fuelwood consumption of an average household decreased from 2880 kg per year to 1728 kg per year when switching from traditional three-stone stoves to ICS [48]. This means, on average 1152 kg of fuelwood is saved per year per household (40% reduction) by the use of ICS. The same study revealed that,

Figure 4. '*Mirt'* fuelwood-efficient stove (Left) with '*Injera*-baking' plate and cover, Ethiopia (Gulilat et al. [72]; Kenya *Ceramic Jiko (KCJ)* charcoal-saving stove (Right) [73].

charcoal consumption of an average household in Tanzania decreased from 1080–370 kg per year when traditional charcoal stoves were replaced by improved charcoal stoves, resulting in an annual charcoal saving of 710 kg per household.

In 2010 a field-testing and survey was carried out by Adkins et al. [91] to evaluate the fuelwood use efficiency of two popular ICSs (*Ugastove* and *StoveTec*) in rural Uganda. The results showed 46% fuelwood savings for *Ugastove*, and 38% fuelwood savings for *StoveTec*. Estimating the expected fuelwood savings per year, they found that the use of an improved biomass cook stove saves on average 530 kg of fuelwood per household per year. The authors emphasized that in a region where scarcity of fuel has become a serious problem, the observed fuelwood savings can have considerable impact in reducing deforestation and forest degradation. These findings demonstrate that the environmental impacts of ICS in reducing pressure on forest resources and enhancing climate change mitigations at local levels are substantial and quantifiable.

3.3.3. Solar home systems and solar cookers

Environmental impacts of large-scale solar power installations are well documented [99,100]. In contrast, literature on the environmental implications of small-scale solar technologies such as SHS, solar cookers and solar PV-water pumps particularly in sub-Saharan Africa is scant. The conventional wisdom is that solar appliances such as solar cookers reduce the use of traditional biomass fuels thus alleviating forest degradation and emissions of harmful GHGs. In this regard, a study by Nandwani in 1996 had projected that, if only 5% of the people who faced fuel shortage in Costa Rica in the year 2005 were to use solar box cookers; about 16.8 million tonnes of fuelwood could have been saved from the use of the solar cookers [101]. This amounts to 38.4 million tonnes of CO_2e emission potentially prevented by using solar energy. He concluded that, solar cookers provide remarkable potential in aiding the solution for the fuel crisis especially in developing countries.

Similarly, a study by Kumar and Kandpal [102] in India found that for areas with an average solar radiation of 5.5 kWh m^{-2}, the net annual CO_2e emission mitigation potential for a 1.8 kWp solar PV pump was about 2085 kg compared to the diesel-operated pumps and about 1860 kg compared to the petrol operated pumps. In contrasts, the application of Solar PV technologies in East Africa is largely limited to electricity generation for lighting and water heating purposes. With virtually zero GHGs emissions, solar PV technologies can indeed provide electricity for millions of rural off-grid households, schools and clinics. Doing so, solar PV technologies can help reduce the negative environmental impact from burning of fossil fuels for lighting and heating purposes.

However, Karekezi and Kithyoma [43] contend that despite growing efforts for widespread dissemination of solar PV technologies in rural East Africa; electricity generation from solar PV has little contribution to reducing and replacing the dependence on biomass fuels for cooking. They argue that given the continuing overreliance on biomass fuels in the region, PV technology does not help to tackle the inefficient biomass energy use by rural households. They suggest that East African states need to inject substantial amount of investment on alternative biomass-energy efficient technologies for significant positive impact on environmental protection and sustainable energy security. Apart from the negligible GHGs emissions, solar energy technologies can also have some negative environmental impacts on the land use, biodiversity and users of the technology. PV modules when especially used at large-scale can lead to destruction of natural ecosystem, resulting in local land use change and fragmentation of sensitive ecosystems [100]. Another potential environmental damage from solar PV cells is that solar modules contain some toxic substances [100] and the possibility of accidental

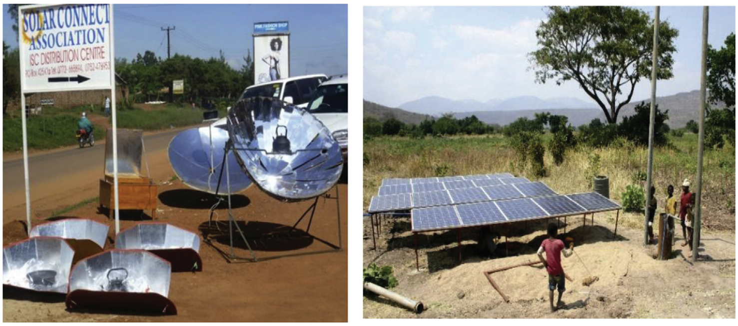

Figure 5. (Left) Solar cookers at Solar Connect distribution center in Kampala, Uganda (SCI [78]); (right) Solar PV water pumping in Tanzania (Solar Hope Foundation [79]).

release of such chemicals to the soil and water systems can pose great threat to the environment and health of local communities.

3.4. Impact on deforestation and climate change mitigation at national and regional levels

Based on the empirical evidences we found in the studies reviewed, we established conservative estimate of the total woody biomass and CO_2e emissions that can be saved by the domestic biogas plants and ICS disseminated up to now in each of the four countries. To do that, two important assumptions were made. First, because categorical data on the exact number of fuelwood- and- charcoal-burning ICS was not available for any of the four countries, all ICS were considered as fuelwood-burning cook-stoves. This assumption avoids potential overestimation of total biomass saved by ICS as the fuel-saving efficiency of wood-burning stoves is much lower than charcoal-burning stoves when measured in terms of total wood equivalent [14,92]. Second, since the performance of biogas plants and ICS varies among studies within each country due to several factors, average fuelwood savings per biogas plant and ICS per household per year were estimated for each country from findings of primary/field studies. However, reductions in fossil fuels consumption from use of the biogas plants and ICS were not considered due to lack of sufficient data. The above assumptions, besides providing conservative estimate, compensate the potential miscalculation of wood savings from SRETs that were disseminated but are not currently functional or not in use.

Accordingly, the household level charcoal savings per biogas and ICS were converted to fuelwood in order to quantify the total wood substituted per biogas plant or ICS per household per year. For this purpose, the FAO [103] charcoal to dry wood conversion rate (1 kg dry wood provides 0.15 kg of charcoal) for traditional kilns in sub-Saharan Africa was used. Subsequently, the average quantity of wood saved per biogas and ICS was computed for each country. The results were used as standard to estimate the total wood saved from each technology per year in each country. In order to convert the total wood-saved by the biogas and ICS disseminated to CO_2e emissions prevented in each country, the IPCC [104] conversion factor of fuelwood from dry weight to CO_2 equivalent (1 kg fuelwood emits 1.83 kg of CO_2e) was used.

The results (see Table 2) show that the 15,000 biogas plants installed in Ethiopia can save about 0.071 million tonnes of wood and 0.13 million tonnes of CO_2e emission per year. In Kenya, the 17,500 biogas plants installed have the potential to save up to 0.064 million tonnes of wood and 0.117 million tonnes of CO_2e emissions per year. Similarly, for Tanzania, the 12,000 biogas plants installed can save up to 0.0645 million tonne of wood and 0.118 million tonne of CO_2e emissions per year. For Uganda, the 6100 biogas plants installed are expected to save about 0.0098 million tonne of wood fuel and 0.018 million tonne of CO_2e emissions per year.

In the same way, the average quantity of wood fuel consumption reduced by one ICS was estimated from first-hand field studies reviewed and the total annual woody biomass saving potential of the improved cook stoves disseminated and assumed to be currently in use in each country was estimated (see Table 3). According to our rough estimates, about 3.03 million tonnes of wood and 5.54 million tonnes of CO_2e emissions is saved annually by the 3.3 million ICS assumed to be currently in use in Ethiopia. In Kenya, the 1.3 million ICS disseminated have the potential to save 1.76 million tonnes of wood fuel and 3.21 million tonne of CO_2e emissions per year. The estimates for Tanzania show that, the 1.2 million ICS disseminated can save about 1.38 million tonne of woody biomass that corresponds to 2.53 million tonnes of CO_2e emissions. In contrast, the 561, 000 ICS disseminated in Uganda between 2005 and 2014 have an estimated potential of saving 0.297 million tonne of woodfuel that amounts to 0.544 million tonne of CO_2e emissions per year.

Aggregating the total wood-fuel-saving potentials of the biogas plants and ICS for each country resulted in the numbers shown in Fig. 6. According to this conservative and rough estimation, if all the biogas plants disseminated and ICS assumed to be in use in Ethiopia are efficiently utilized, they have the combined potential of saving about 3.10 million tonnes of wood per year. This corresponds to about 5.67 million tonnes of CO_2e emission reduction per annum. In Kenya, biogas plants and ICS combined can save about 1.82 million tonnes of wood and 3.33 million tonnes of CO_2e emission annually. Similarly, about 1.45 million tonnes of wood and 2.65 million tonnes of CO_2e emissions is expected to be saved by the biogas plants and ICS disseminated so far in Tanzania. The fewer biogas plants and ICS disseminated in Uganda have the combined potential of saving about 0.31 million tonne of wood and 0.562 million tonne of CO_2e per year.

These estimates indicate that the potential of SRETs to reduce and replace consumption of biomass fuel and emission of CO_2 is considerable at national levels. In the long-term especially, SRETs can play critical role in helping countries in the region achieve sustainable forest management and climate change mitigation from reduced deforestation, sustained biomass supply, increased forest carbon stocks and welfare and health benefits to users.

However, analyzing these potential wood-savings in the context of the total annual biomass energy consumptions of each country provides a different perspective. For instance, the Ethiopian biomass energy strategy and action plan [105] has reported that about 60 million tonnes of biomass is consumed for energy purposes per year in the country, of which 81% of it is used as fuelwood for cooking. Compared to this annual demand for biomass energy, the expected savings from currently disseminated biogas and ICS in the country can only substitute 5.2% the total demand. In Kenya, a study published by the Ministry of Energy shows that in 2000 about 31.617 million tonnes of wood was consumed for energy purposes mainly in the form of firewood and charcoal [53,106]. More recently, Njogu [14] reported that the demand for biomass energy in Kenya in 2011 was about 40.5 million tonnes. When this demand is compared with the 1.82 million tonnes expected total wood saving from the biogas plants and ICS disseminated; the potential energy substitution accounts only for 4.5% of the demand.

In 2005, Tanzania's total annual wood fuel consumption was estimated at about 20 million tonnes per year [107]. Even with this noncurrent data, the estimated total wood savings from the biogas plants and ICS can only offset about 7.2% of the national demand. According to the biomass energy strategy of Uganda [52], the total biomass energy consumption of Uganda is about 44 million tonnes per year, of which Uganda's forests and trees can only sustainably supply 26 million tonnes per year. Based on the approximately estimated 0.3 million tonnes of fuelwood savings from the biogas plants and ICS per year, the energy substitution in Uganda is even less than 1% of the national biomass

Table 2

Estimated woodfuel and CO_2e emission savings form biogas plants at national levels.

Country	No of biogas plants installed	Average quantity of wood-fuel saved/plant/year in tonne	Total estimated wood-fuel saved/year in tonne	Total CO_2 emission reduction/year in tonne
Ethiopia	15,000	4.719	70,791	129,548
Kenya	17,500	3.650	63,875	116,891
Tanzania	12,000	5.376	64,512	118,057
Uganda	6100	1.610	9821	17,972

Table 3
Estimated total fuelwood and CO_2 emission savings form ICS at national levels.

Country	Estimated No of ICS distributed/ currently in use	Average quantity of wood fuel saved/ICS/ year in tonne	Total estimated wood-fuel saved in tonne/year	Total CO_2e emission reduced per year in tonne
Ethiopia	3,300,000	0.918	3,029,400	5,543,802
Kenya	1,300,000	1.350	1,755,000	3,211,650
Tanzania	1,200,000	1.152	1,382,400	2,529,792
Uganda	561,000	0.530	297,330	544,114

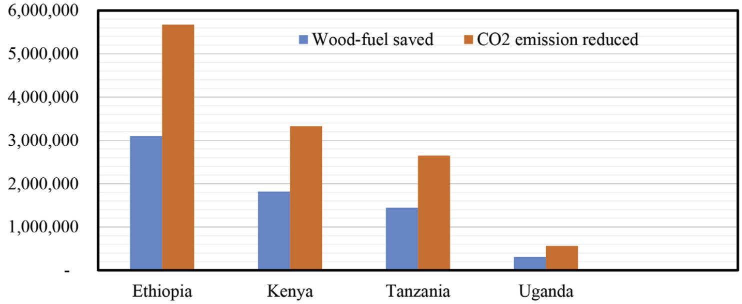

Fig. 6. Estimated annual wood fuel consumption and CO_2e emission savings from biogas plants and ICS at national levels in tonne per year.

energy demand.

These results imply that the current potential impact of SRETs in inducing substantive decline in biomass energy consumption and deforestation vis-à-vis environmental degradation and GHGs emissions at national and regional levels remains very small. This is despite the significant positive results observed at household and local levels in terms of fuelwood-savings and CO_2e emission reductions. Our estimations did not include environmental benefits from other SRETs such as solar PV micro-grids; nor did we account the environmental benefits from large-scale renewable sources such as biofuels and hydropower plants in these countries. Nevertheless, the technologies we considered represent the major SRETs currently disseminated in each country especially for cooking purposes. As such, they provide an overview and insight on the level of significance and potential impact that SRETs have at national and regional levels in terms of mitigating deforestation and climate change. Unleashing the potentials of SRETs and achieving broad-based and lasting impact at national and regional levels requires addressing some critical barriers and setbacks discussed hereunder. Table 4 summarizes the research questions and the main findings of the review.

3.5. Lessons learned, barriers and alternative options

Africa has the potential of supplying its own energy demand as well as exporting global-capacity renewable energy to the world. However, number of obstacles are holding back the sustainable energy development of the energy resource-rich continent [24]. The major barriers for the development of SRETs in East Africa and the lessons learned from the analysis of the evidence in this review are discussed hereafter and summarized on Table 5.

3.5.1. Inadequate policy priority and weak institutional capacity

SRETs in East Africa has not yet received adequate policy support, and budgeting from respective national governments [24]. In countries where enabling policies are formulated, implementation of these polices remains weak. As a result, much of the effort in disseminating SRETs in the region still heavily depends on international donors and subsidy. In Ethiopia for instance, Wolde-Ghiorgis [108] noted that between 1990 and 2000, government investment in large-scale hydropower generation has tripled whereas expenditure on small-scale and alternative renewable energy has declined from 1% of total national energy sector expenditure in 1990 to 0.1% of total expenditure of the energy sector in year 2000. In addition to the heavy reliance on external funding, most East African states have very low institutional capacity with insufficient human resources for operating and monitoring the technologies [109,110]. Addressing these problems requires enacting focused and context-specific policies, allocating adequate budget, and building the capacity of the sector along with providing candid support for private sector.

3.5.2. Lack of innovative financing mechanisms

Another major obstacle facing SRETs especially in rural East Africa is the high initial cost of most of the technologies, and lack of access to long-term and sustainable financing mechanisms [36]. For most of the poor households in the region, the high initial investment cost of many of the SRETs denotes a major barrier preventing them from purchasing the technologies [24,111]. The solution involves bestowing priority to the establishment of innovative and sustainable financing programmes that would make SMRETs accessible to consumers including the very poor at affordable prices while ensuring that the sector remains sustainable [35].

In this line, Mengistu et al. [112] strongly recommend that provision of financial and non-financial incentives to households is vital to enhance the dissemination of the technologies. Such financial incentives could include facilitating long-term credit services with the help of micro-finance institutions, commercial banks, Savings and Credit Cooperatives, local community development agencies and the private sector. Laramee and Davis [34] have suggested that considering the significant GHG emission offsets that adoption of biogas technology could effect in the region, accessing carbon emissions reduction (CER) financing through the Clean Development Mechanism (CDM) is worth considering.

3.5.3. Lack of local technical capacity, monitoring and evaluation

One of the critical requisite to effective tapping of the potential of SRETs is ensuring households actually use the technologies once installed. Studies show that following the introduction of ICS, many households in the region and Africa at large have continued to use the

Table 4
Summary of the research questions and the main findings of the review.

Research questions	Summary of main findings
RQ1. What is the trend of adoption and use of SRETs in East Africa?	– The adoption and use of SRETs in East Africa is growing steadily especially over the last decade – Between 2005 and 2015 alone, an estimated total of 50,600 biogas plants; 6,361,000 improved cook stoves, 576,000 solar home systems were disseminated in the four countries studied (Ethiopia, Kenya, Tanzania and Uganda)
RQ2. Are users of SRETs consuming less biomass and fossil fuels than before/ non-adopters?	– Yes! Households using SRETs have substantially reduced their consumption of traditional biomass and fossil fuels. – On average a biogas user household consumes 1.61–5.376 tonnes less fuelwood and 0.818 tonnes less charcoal, and 48 L less kerosene per year compared to a household who is not using biogas technology – A household that has adopted an improved cook stove consumes up to 1.152 tonnes of less fuelwood and up to 0.71 tonnes of less charcoal per year compared to those households using traditional or open-fire stoves.
RQ3. How significant is the impact of SRETs in reducing CO_2e emissions of households	– The review shows that reductions in wood fuel consumption of household as a result of the biogas plant amounts to an average emissions cut of 1.90–5.825 tons of CO_2e per household per year – Similarly, on average, a household with an ICS emits 75% less CO_2e compared to the one using traditional stoves.
RQ4. Are SRETs leading to household energy transition towards clean and renewable sources in East Africa?	– The adoption of biogas technology and ICS has prompted partial household energy transition from wood fuel-based to renewable and cleaner sources. – However, most households (≈75%) who have adopted one or more SRETs still depend multiple fuels including the traditional biomass and fossil fuels with more than one type of cooking fuel as opposed to complete abandonment of traditional fuels – The results implies that traditional fuels will remain the main energy source of the majority of rural and peri-urban households in the region. As such, access to SRETs may not lead to swift transition to clean and renewable energy sources at least in the near future.
RQ5. How significant is the impact SRETs in reducing deforestation and forest degradation at national and regional levels?	– In spite of the substantial household level effects of SRETs in reducing wood fuel consumption and CO_2e emissions; their aggregated impact in reducing deforestation and forest degradation at national and regional levels remains limited. – The combined potential of all the biogas plants and ICS disseminated hitherto in the four countries studied appear to save from 0.307 to 3.10 million tonnes of wood fuel. – Yet, this reduction in traditional wood fuel consumption can only offset 1–7% of the national biomass energy demands of each country.
RQ6. How significant is the impact of use of SRETs in reducing CO_2e emissions and mitigating climate change at national and regional levels?	– Similarly, our conservative estimates based on the evidence in the review showed that the domestic biogas and improved cook stoves distributed up to now have a combined potential of saving the emission of 0.562–5.673 million tonnes of CO_2e per country per year. – However, at national and regional levels the CO_2e emission reduction because of SRETs does not offset more than 4% of the national emissions of each country.
RQ7. What are the major barriers and setbacks hindering the diffusion and efficient use of SRETs in the region?	– Inadequate policy priority and weak institutional capacity – Lack of innovative financing mechanisms – Lack of local technical – capacity, monitoring and evaluation – Lack of awareness and experience sharing platforms – Misunderstanding of ‘one size fits all’ – Lack of cross-sectoral integration and policy alignment

traditional three-stone fire for cooking [56]. Mengistu et al. [112] reported that from the total number of biogas plants installed up until 2009 in Ethiopia, about 60% were not functional after a short period of installation. The main reasons according to Mengistu et al. [112] were lack of technical capacity of the biogas users to maintain the plants due to lack of technical assistance and adequate pre- and post-adoption training of users. This is also strongly linked with the general lack of skilled manpower in the field in the countries coupled with lack of monitoring and follow-ups of the plants by local and national energy agencies and technology suppliers. To alleviate the problem, Njoroge [109] and Mengistu et al. [112] recommend setting up maintenance and aftersales services for SRETs including availing skillful and standby technicians at reasonable distances to users. Implementing short-term and long-term training programs designed at creating adequate locally trained manpower within the rural settings with the necessary knowledge and skills is critical [43].

3.5.4. Lack of awareness and experience sharing platforms

Low awareness and lack of knowledge to majority of targeted end-users about SRETs is another major barrier to the adoption and poor ownership responsibility of users [110]. Lack of information exchange, sensitization and experience - sharing mechanisms on what works and what does not within and between communities, districts and countries is a formidable barrier that is often underestimated [25]. In remote pastoral and agro-pastoral areas of the region in particular, local people still lack the information and awareness about available SRETs, benefits and costs and means of acquiring them. Yadav [113] suggests that setting up national umbrella body and local networks with the main task of coordinating and stimulating interaction and knowledge transfer between rural households, researchers, technology suppliers, and operators is key. Establishing national and inter-regional research and institutional capacity building network is also worth engaging.

3.5.5. The misunderstanding of ‘one size fits all’

Successful dissemination of SRETs should take in to account the existing local knowledge, appropriateness of the technology and designs with reference to local cooking preferences and cultures, the availability of sufficient renewable fuel stock, and the affordability, ease of use, efficiency, health and environmental implications of the technologies. Failure to understand the local context inevitably leads to slow adoption or even dis-adoption of SRETs as evidenced by the findings of Lwiza et al. [63] in Uganda's biogas sector. As noted by Tesfay et al. [88], the adoption and utilization of solar box cookers in Ethiopia has been very limited in part because the technologies were unable to bake ‘Injera’- Ethiopia's big round flat bread. This implies that effective diffusion of SRETs for optimal environmental and energy

Table 5
Summary of the major barriers, lessons and alternative solutions.

Major barriers	Lessons learned	Suggested solutions
Inadequate policy priority and weak institutional capacity	– Unsatisfactory policy support – Where enabling policies are formulated, planning and implementation remains weak. – Weak institutional capacity, inadequate funding & human resource –Dependence on donor funding and government subsidy.	– Enacting prudent and working policies – Providing candid and sustained support for private investment. – Creating local/national research and institutional capacity building centers
Lack of innovative financing mechanisms	– High initial cost of most of the SRETs – Lack of access to long-term credit and/or high interest rates – Lack of innovative and sustainable financing programmes to make SMRETs accessible to the very poor at affordable prices	– Provision of financial and non-financial incentives – Facilitating long-term credit services with the help of micro-finance institutions, banks, Savings and Credit Cooperatives
Lack of local technical capacity, monitoring and evaluation	– Lack of proper management and maintenance of the technologies – Lack of technical assistance and adequate pre/post-adoption training – Lack of spare parts – Lack of skilled manpower in the sector	– Ensure the technologies are functional once installed through monitoring, follow up and technical support. – Providing short-term and long-term trainings
Lack of awareness and experience sharing platforms	–Low awareness of target end-users about the technologies – Poor ownership feeling of users as result of donor funding and/or subsidy – Lack of information exchange and experience - sharing mechanisms	– Set up national and local centers for creating awareness, coordinating interaction & knowledge transfer between users, suppliers, and operators
Misunderstanding of 'one size fits all'	– Dissemination of SRETs hardly takes into account local knowledge, suitability of the technology and designs with reference to local cooking preferences, cultures, fuel stock availability, livelihood, ease of use, household capacity, etc.	– Conduct rigorous feasibility study and selection criteria of suitable technologies as opposed to politically motivated 'top-down' mass adoption campaign
Lack of cross-sectoral integration and policy alignment	– No meaningful integration among the diverse agencies, stakeholders and the private sector to effectively develop and use SRETs in most of the countries – Direct link between technology companies supplying the SRETs and local users is almost nonexistent.	– Creating cross-sectoral integration and multi-stakeholder cooperation platforms with sound networking and information sharing systems

benefits entails rigorous feasibility study and selection and development of the technologies as opposed to politically motivated 'top-down' mass dissemination campaign. In essence, innovative and effective dissemination strategies for SRETs necessitates fundamental understanding of what end-users need and can take in terms of utility while also meeting the goals of improved efficiency and reduced CO_2e emissions.

3.5.6. Lack of cross-sectoral integration and policy alignment

Kamp and Forn [114] stated that while the national biogas programme of Ethiopia (NBPE) has brought in diverse set of agencies and stakeholders to the implementation of the programme, their alignment is weak and the private sector is not involved at all. Kebede and Mitsufuji [86,87] stressed that the integration, cooperation and coordination among various actors, ministries, district and local level rural energy development and promotion agencies and environmental protection bureaus is very weak and often exhibiting competing goals. Examining the diffusion of Solar PV in Ethiopia, Kebede and Mitsufuji [87] explained that a direct link between technology companies supplying the solar PVs and local stakeholders and users is almost nonexistent. The solution is apparent but not easy, creating cross-sectoral integration and multi-stakeholder cooperation with sound networking and information sharing systems at all levels.

4. Conclusions

This review has shown that adoption and utilization of small-scale renewable energy technologies is growing in East Africa. Evidently, about 15, 000 biogas plants in Ethiopia; 17, 500 in Kenya; 12, 000 in Tanzania and 6100 in Uganda were installed between 2005 and 2015. Similarly, about 3,300,000 improved cooking stoves in Ethiopia; 1,300,000 in Kenya; 1,200,000 in Tanzania and 561,000 in Uganda were distributed during the same period. Comparably, 40, 000 Solar Home Systems in Ethiopia; 445,000–470,000 in Kenya; 65,000 in Tanzania and 26,000 in Uganda were disseminated between 2005 and 2015. As a result, households and small-businesses utilizing these technologies are cutting-back their fuelwood, charcoal and fossil fuel consumptions considerably. The new access to a more efficient and cleaner energy services is reducing households' dependence on traditional wood fuels, and emissions of sizeable amount of CO_2 at local levels. The evidence indicates that adoption and use of SRETs has partially induced household energy transition from a predominantly wood fuel-based to a new energy mix where the share of clean and renewable energy is sizeable. This lays the ground for sustainable and low carbon development at local level. However, the findings of the review also revealed that households using SRETs did not completely abandon wood fuels implying that access to SRETs may not lead to a complete relinquishment of traditional biomass and swift leapfrogging to clean and renewable energy in the near future.

With respect to environmental conservation and climate change mitigation, the empirical evidences show that the adoption and use of SRETs such as biogas and improved cooking stoves is considerably reducing the pressure on forest and other bio-energy resources. The review showed that the partial or complete substitution of fuelwood and charcoal by the clean energy from SRETs is reducing tree-felling and firewood collection for domestic energy thus lessening deforestation and degradation of woodlands by households. The decrease in the burning of wood and charcoal and increase in the conservation of standing trees helps cutback household emissions of GHGs and reduces the health risk of women and children from the biomass smoke.

However, at national and regional levels, the significance and magnitude of impact of the SRETs disseminated so far in mitigating deforestation and climate change appears limited and undeveloped. According to the results of the conservative estimation made, the total woodfuel and CO_2e emissions saving potentials of the biogas plants installed in Ethiopia was only about 0.071 million tonnes of wood and 0.129 million tonnes of CO_2e per year respectively. In Kenya, the estimated woodfuel and CO_2e emissions saving potential of the biogas plants installed was only about 0.064 million tonnes of wood and 0.117 million tonnes of CO_2e respectively. In Tanzania, the total woodfuel and CO_2e emission potential savings from the biogas plants disseminated so far were estimated at 0.065 million tonnes of wood and 0.118 million tonnes of CO_2e per year respectively. In the same way, the potential woodfuel and CO_2e emission savings from the biogas plants disseminated in Uganda were estimated at 0.009 million tonnes of wood and 0.018 million tonnes of CO_2e emissions per year respectively. In contrast, the estimated woodfuel and CO_2 emission savings of improved cook stoves in each country was substantial. According to the results of the estimations, the total woodfuel and CO_2e emissions saving potential of the ICS distributed in Ethiopia was about 3.03 million tonnes of wood and 5.54 million tonnes of CO_2e per year respectively. In Kenya, the total estimated woodfuel and CO_2e emissions savings of the ICS disseminated was about 1.76 million tonnes of wood and 3.21 million tonnes of CO_2e emissions per year respectively. In Tanzania, the ICS disseminated were estimated to save up to 1.38 million tonnes of wood and 2.53 million tonnes of CO_2e emissions per year respectively. On the other hand, the ICS distributed in Uganda were estimated to save up to 0.30 million tonnes of wood and 0.54 million tonnes of CO_2e emissions per year respectively.

The review suggests that building on the current promising local level effects and achieving greater and lasting impacts at national and regional levels entails understanding and addressing the critical barriers and gaps in a holistic manner. To that end, the study recommends that national governments in the region should formulate prudent policies and provide candid support to the sector including the provision of financial and non-financial incentives, availing subsidy, long-term credit services and soft loans to enhance the widespread adoption of the SRETs technologies. Moreover, ensuring that the technologies are operational once installed by setting up maintenance service centers with skilled and standby technicians, and proper monitoring and follow up services is critical to effectively utilize the SRETS and avoid negative spillover effects on potential users. Strengthening the institutional, technical, logistical and human resource capacity of district and local level SRETs promotion and dissemination offices and staffs is instrumental to enable them create the awareness of the communities and provide timely trainings, maintenance services and establish local experience-sharing platforms. This will facilitate knowledge transfer between users, non-users, suppliers, and technicians. Further, establishing viable cross-sectoral integration and multi-stakeholder cooperation including the private sector at national and local levels is crucial should SRETs play a major role in the energy regime of households in East Africa.

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References

[1] African Development Bank Group (AfDB). East Africa Regional Resource Centre (EARC) Report 2014 2014 https://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/AfDB_Partner_of_Choice_for_East_Africa_-_EARC_Report_2014.pdf/ accessed 15.08.17.

[2] The World Bank. World Development Indicators database, population. 2016http://databank.worldbank.org/data/download/POP.pdf accessed 28.04.17.

[3] Deutsche Gesellschaft für Internationale Zusammenarbeit (GTZ). Regional Reports on Renewable Energies 30 Country Analyses on Potentials and Markets in: West Africa (17) East Africa (5) Central Asia (8). Energy-policy Framework Papers Germany: Eschborn; 2009http://www.ecreee.org/sites/default/files/event-att/gtz_re_in_developing_countries.pdf/ accessed 20.08.17.

[4] International Energy Agency (IEA). World Energy Outlook. 2014https://www.iea.org/publications/freepublications/publication/WEO2014.pdf/ accessed 19.03.17.

[5] United Nations Statistics Division. Energy Statistics Database: Electricity, net installed capacity of countries. http://data.un.org/Data.aspx?d = EDATA&f = cmID%3AEC; 2014 accessed 16.05.17.

[6] The World Bank. Rural population (% of total population) by country. http://data.worldbank.org/indicator/SP.RUR.TOTL.ZS; 2015 accessed 16.05.17.

[7] International Energy Agency (IEA). Electricity Access Database -Africa. 2015www.worldenergyoutlook.org/media/.../WEO2015Electricityaccessdatabase.xlsx accessed 19.04.17.

[8] Beyene AD, Koch SF. Clean fuel-saving technology adoption in urban Ethiopia. Energy Econ 2013;36:605–13.

[9] Seidel A. Charcoal in Africa: Importance, problems and possible strategies. Germany: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ). Eschborn; 2008.

[10] Karekezi S. Poverty and energy in Africa—a brief review. Energy Policy 2002;30:915–9.

[11] Ndegwa GM, Nehren U, Grüninger F, Iiyama M, Anhuf D. Charcoal production through selective logging leads to degradation of dry woodlands: A case study from Mutomo District, Kenya. J Arid Land 2016;8:618–31.

[12] Mengistu MG, Simane B, Eshete G, Workneh TS. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. Renew Sustain Energy Rev 2015;48:306–16.

[13] Gebreegziabher Z, Cornelis VKG, Soest DV. Stove adoption and implications for deforestation and Land degradation: The case of Ethiopia. In: Gebeyehu W, Alemu G, editors. The Ninth International Conference on the Ethiopian Economy. Ethiopian Economic Association (EEA): Addis Ababa, Ethiopia. 2011.

[14] Njogu PK. Adoption of Energy-Efficient Woodstoves and Contribution to Resource Conservation in Nakuru County MSc thesis Nairobi, Kenya: Kenyatta University; 2011http://irlibraryku.ac.ke/bitstream/handle/123456789/3682/Njogu%2C%20Paul%20Kuria.pdf?sequence = 3&isAllowed = y/ Accessed 01.06.17.

[15] Mwampamba TH. Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. Energy Policy 2007;35:4221–34.

[16] Intergovernmental Panel on Climate Change (IPCC). Climate Change: Synthesis Report, IPCC Fourth Assessment Report Cambridge, UK: Cambridge University Press; 2007https://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter9.pdf/ Accessed 10.07.17.

[17] Bekele M, Wassie YT, Tolera M. The Charcoal Industry Assessment of Ethiopia: Policy and Institutional Restructuring for Sustainable Charcoal. Ministry of Environment; 2016. Forest and Climate Change (MEFCC), Supported by Global Green Growth Institute (GGGI); Republic of Ethiopia, Addis Ababa [unpublished document)].

[18] Iiyama M, de Leeuw JM, Dobie P, Jamnadass RH, Mowo GJ, Ndegwa GM, et al. Charcoal as a driver of dryland forest degradation and suggestions on how to make it sustainable in Africa? World Agroforestery Centre. Kenya: ICRAF) Nairobi; 2014https://www.worldagroforestry.org/publication/charcoal-driver-dryland-forest-degradation-and-suggestions-how-make-it-sustainable/ accessed 16.07.17.

[19] Kirubi C, Wamicha WN, Laichena JK. The effects of woodfuel consumption in the ASAL areas of Kenya: The case of marsabit forest. Afr J Ecol 2000;38:47–52.

[20] Hofstad O. Woodland deforestation by charcoal supply to dar es Salaam. J Environ Econ Manag 1997;33:17–32.

[21] Felix M, Gheewala SH. A review of biomass energy dependency in Tanzania. Energy Procedia 2011;9:338–43.

[22] Bailis R, Ezzati M, Kammen DM. Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa. Science 2005;308:98–103.

[23] World Health Organization (WHO). Indoor Air Pollution: Environmental burden of disease for selected risk factors per year (estimates for Ethiopia). 2009 Geneva, Switzerland http://www.who.int/quantifying_ehimpacts/national/countryprofile/ethiopia.pdf?ua = 1/ accessed 19.08.17.

[24] Lior N. Sustainable energy development: The present (2011) situation and possible paths to the future. Energy 2012;43(1):174–91.

[25] Netherlands Development organization (SNV). Africa biogas and clean cooking: conference report. Addis Ababa, Ethiopia 5–7 April 2016 Available on: https://www.slideshare.net/FredMarree/report-of-the-africa-biogas-and-clean-cooking-conference-57-april-2016-62612480, Accessed date: 13 April 2017.

[26] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Energizing Development (EnDev)- Ethiopia. 2017https://endev.info/content/Ethiopia accessed 11.04.17.

[27] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Energizing Development (EnDev)- Kenya. 2017https://endev.info/content/Kenya accessed 13.04.17.

[28] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Energy from biogas and biomass: Market opportunities in Kenya. 2014https://www.giz.de/fachexpertise/downloads/2014-de-pep-informationsveranstaltung-bio-kenia-mugenya.pdf/ accessed 11.04.17.

[29] National Biogas Programme of Ethiopia (NBPE). Results-based approaches to support the national biogas programme of Ethiopia. London: Report for SNV. Vivid Economics; 2014.

[30] Dresen E, DeVries B, Herold M, Verchot L, Müller R. Fuelwood savings and carbon emission reductions by the use of improved cooking stoves in an afromontane forest, Ethiopia. Land 2014;3:1137–57.

[31] Amare ZY. The benefits of the use of biogas energy in rural areas in Ethiopia: A case study from the Amhara National Regional State, Fogera district of Northern Ethiopia. Biomass Bioenergy 2015;90:131–8.

[32] Tajebe L. Bio-Gas Technology adoption in rural Ethiopia: Its effect on the crisis of deforestation. J Energy Technol Policy 2016;6(1).

[33] Mengistu MG, Simane B, Eshete G, Workneh TS. The environmental benefits of domestic biogas technology in rural Ethiopia. Biomass Bioenergy 2016;90:131–8.

[34] Laramee J, Davis J. Economic and environmental impacts of domestic bio-digesters: Evidence from Arusha, Tanzania. Energy Sustain Dev 2013;17:296–304.

[35] Mwakaje AG. Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. Renew Sustain Energy Rev

2008;12:2240–52.
[36] Menya E, Alokore Y, Ebangu BO. Biogas as an alternative to fuelwood for a household in Uleppi sub-county in Uganda. Agric Eng Int: CIGR J 2013;15:50–8.
[37] Ghimire PC. SNV supported domestic biogas programs in Asia and Africa. Renew Energy 2013;49:90–4.
[38] Murphy JT. Making the energy transition in rural East Africa: Is leapfrogging an alternative? Technol Forecast Soc Change 2001;68:173–93.
[39] Berhe M, Hoag D, Tesfay G, Keske C. Factors influencing the adoption of biogas digesters in rural Ethiopia. Energy Sustain Soc 2017;7:10.
[40] Lusambo LP. Household energy consumption patterns in Tanzania. J Ecosyst Ecogr 2016;S5(007).
[41] Guta DD. Application of an almost ideal demand system (AIDS) to Ethiopian rural residential energy use: Panel data evidence. Energy Policy 2012;50:528–39.
[42] Mekonnen A, Köhlin G. Determinants of household fuel choice in major cities in Ethiopia. Working Papers in Economics No 399. Göteborg, Sweden: University of Gothenburg; 2009https://gupea.ub.gu.se/bitstream/2077/21490/1/gupea_2077_21490_1.pdf/.
[43] Karekezi S, Kithyoma W. Renewable energy strategies for rural Africa: Is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa? Energy Policy 2002;30:1071–86.
[44] Littell JH, Corcoran J, Pillai V. Systematic Reviews and Meta-Analysis. Oxford University Press; 2008.
[45] Bowler DE, Buyung-Ali LM, Knight TM, Pullin AS. A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health 2010;10:456.
[46] Pullin AS, Stewart GB. Guidelines for systematic review in conservation and environmental management. Conserv Biol 2007;20:1647–56.
[47] Moher D, Alessandro L, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med 2009;6:7.
[48] Kebede E, Kagochi J, Jolly CM. Energy consumption and economic development in Sub-Sahara Africa. Energy Econ 2010;32:532–7.
[49] Schlag N, Zuzarte F. Market Barriers to Clean Cooking Fuels in Sub-Saharan Africa: A Review of Literature. Stockholm Institute of Environment (SIE); 2008https://www.sei-international.org/mediamanager/documents/Publications/Climate/market_barriers_clean_cooking_fuels_21april.pdf accessed 19.06.17.
[50] Gebreegziabher Z. Household Fuel Consumption and Resource Use in Rural-Urban Ethiopia PhD diss The Netherlands: Department of Social Sciences, Wageningen University; 2007http://library.wur.nl/WebQuery/wurpubs/fulltext/31629/ accessed 17.06.17.
[51] Okello CP, Pindozzi S, Faugno S, Boccia L. Development of bioenergy technologies in Uganda: A review of progress. Renew Sustain Energy Rev 2013;18:55–63.
[52] Ministry of Energy and Mineral Development of Uganda (MEMD). Biomass Energy Strategy (Best) Uganda. Government of Uganda: Kampala; 2014http://www.undp.org/content/dam/uganda/docs/UNDPUg2014%20-%20Biomass%20BEST%20Strategy(compressed).pdf/ accessed 23.07.17.
[53] Githiomi JM, Oduor N. Strategies for sustainable wood fuel production in Kenya. Int J Appl Technol 2012;2:10.
[54] Chidumayo EN, Gumbo DJ. The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. Energy Sustain Dev 2012;17:86–94.
[55] Chidumayo EN, Gumbo DJ. The Dry Forests and Woodlands of Africa: Managing for Products and Services. London: Earthscan; 2010.
[56] Nyambane A, Johnson F, Grimsditch G, Ochieng C, von Maltitz G. Environmental, social and economic co-benefits of charcoal substitution with bioethanol in Malawi and Mozambique. Stockholm Environment Institute; 2014http://www.espa.ac.uk/projects/fell-2014-107/ accessed 12.06.17.
[57] Subedi M, Matthews RB, Pogson M, Abegaz A, Balana BB, Oyesiku-Blakemore J, et al. Can biogas digesters help to reduce deforestation in Africa? Biomass Bioenergy 2014;70:87–98.
[58] Bekele M, Tesfaye Y, Mohammed Z, Zewdie S, Wassie YT, Brockhaus M, Kassa H. The context of REDD+ in Ethiopia: Drivers, agents and institutions. Bogor, Indonesia: Center for International Forestry Research (CIFOR); 2015. Occasional Paper No. 127.
[59] World Agroforestry Centre (ICRAF). Charcoal as a driver of dryland forest degradation in Africa? Nairobi, Kenya: ICRAF Factsheet; 2013.
[60] Bailis R. Modeling climate change mitigation from alternative methods of charcoal production in Kenya. Biomass Bioenergy 2009;33:1491–502.
[61] Smith KR. Health impacts of household fuelwood use in developing countries: Forests and Human Health. Rome: Food and Agriculture Organization of the United Nations (FAO); 2006. Unasylva 57.
[62] Wamuyu MS. Analysis of Biogas Technology for Household Energy, Sustainable Livelihoods and Climate Change Mitigation in Kiambu County, Kenya. A PhD thesis and dissertation. Kenya: School of Environmental Studies, Kenyatta University; 2014.
[63] Lwiza F, Mugisha J, Walekhwa PN, Smith J, Balana B. Dis-adoption of household biogas technologies in Central Uganda. Energy Sustain Dev 2017;37:124–32.
[64] Alemayehu YA. Status and benefits of renewable energy Technologies in the rural areas of Ethiopia: A case study on improved cooking stoves and biogas Technologies. Int J Renew Energy Dev 2015;4(2):103–11.
[65] Netherlands Development organization (SNV). Improved-cookstoves-Kenya. 2017http://www.snv.org/project/improved-cookstoves-ics-kenya/ Accessed 8.06.17.
[66] Ministry of Water, Irrigation and Energy of Ethiopia (MoWIE). Updated Rapid Assessment and Gap Analysis on Sustainable Energy for All (SE4All): The UN Secretary General Initiative. Federal Democratic Republic of Ethiopia. 2013https://www.se4all-africa.org/fileadmin/uploads/se4all/Documents/Country_RAGAs/MWH_-_Updated-Rapid_Gap_Analysis.pdf/ Accessed 15.07.17.
[67] Okello V. The Upesi rural stoves project. Boiling point; 2005. 51 http://www.bioenergylists.org/stovesdoc/PracticalAction/bp51-Upesi_stove-project.pdf/. 2005.
[68] Netherlands Development organization (SNV). Improved Cook Stoves Assessment and Testing- ICS Taskforce Tanzania. 2014https://www.tarea-tz.org/storage/app/.../ICS%20Assessment%20and%20Testing.pdf Accessed 07.06.17.
[69] Otieno HO, Awange JL. Energy Resources in East Africa: Opportunities and Challenges. Springer; 2006. https://doi.org/10.1007/978-3-540-35669-1.
[70] Uganda National Household Survey (UNHS). Abridged Report, Uganda Bureau of Statistics. The Government of Uganda. Kampala; 2010.
[71] Kees M, Feldmann L. The role of donor organizations in promoting energy efficient cookstoves. Energy Policy 2011;39:7595–9.
[72] Gulilat A, Girma W, Wedajo T, Tessema Y. Mirt Stove Ethiopia-Stove Testing Results: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) report. Addis Ababa, Ethiopia; 2011.
[73] Bahn N. Branding the Unbranded: The story of Cookswell Jikos. 2015 Kenya http://nitibhan.com/2015/03/24/branding-the-unbranded-the-story-of-cookswell-jikos-kenya/ Accessed 10.07.17.
[74] Karekezi S. Renewables in Africa—meeting the energy needs of the poor. Energy Policy 2002;30:1059–69.
[75] Dekker J, Nthontho M, Chowdhury S, Chowdhury SP. Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa. Int J Electr Power Energy Syst 2012;40(1):104–12.
[76] Ngetha H, Sasakia M, Taheria M, Mathenge S. Energy Transitions for the rural community in Kenya's central highlands: Small scale solar powered systems. Energy Procedia 2015;79:175–82.
[77] Hansen UE, Pedersen MB, Nygaard I. Review of solar PV policies, interventions and diffusion in East Africa. Renew Sustain Energy Rev 2015;46:236–48.
[78] Solar Cookers International (SCI). Solar Connect Association, Kampala Uganda. 2012http://solarcooking.wikia.com/wiki/Uganda/ Accessed 04.07.17.
[79] Solar Hope Foundation (SHF). USA: Oregon Institute of Technology; 2014https://www.indiegogo.com/projects/bring-light-to-tanzania-solar-hope#/ Accessed 15.07.17.
[80] Ondraczek J. The sun rises in the east (of Africa): A comparison of the development and status of solar energy markets in Kenya and Tanzania. Energy Policy 2013;56:407–17.
[81] Kenya Climate Innovation Center (KCIC). Kenya solar PV market assessment. 2015 Kenya https://www.kenyacic.org/sites/default/files/publications/KCIC%20Solar%20Survey-3.pdf Accessed 25.03.17.
[82] Innovation and Renewable Electrification in Kenya (IREK). A desk assessment on the overviews of current solar and wind energy projects in Kenya. 2015 Nairobi, Kenya http://irekproject.net/files/2015/11/Solar_and_wind_energy_projects_Kenya-IREK1.pdf Accessed 12.07.17.
[83] Solar Energy Foundation. Ensuring Access to Affordable, Reliable, Sustainable and Modern Energy for All (SDG 7). Experiences and Best Practices in Ethiopia. 2016https://sustainabledevelopment.un.org/content/documents/22747Solar%20Energy%20Foundation%20experiance%20and%20best%20practices.pdf Accessed 13.07.17.
[84] Sarakikya H, Ibrahim I, Kiplagat J. Renewable energy policies and practice in Tanzania: Their contribution to Tanzania economy and poverty alleviation. Int J Energy Power Eng 2015;4(6):333–41.
[85] International Renewable Energy Agency (IRENA). Solar PV in Africa: Costs and Markets. 2016https://www.irena.org/DocumentDownloads/Publications/IRENA_Solar_PV_Costs_Africa_2016.pdf Accessed 04.06.17.
[86] Kebede KY, Mitsufuji T, Yemiru BS. Diffusion of solar cookers in Africa: Status and prospects. Int J Energy Technol Policy 2014;10(3–4):200–20.
[87] Kebede KY, Mitsufuji T. Diffusion of solar innovations in Ethiopia: Exploring systemic problems. Int J Technol Manag Sustain Dev 2014;13:53–72.
[88] Tesfay AH, Kahsayb MB, Nydala OJ. Solar powered heat storage for injera baking in Ethiopia. Energy Procedia 2014;57:1603–12.
[89] Hosier RH, Dowd J. Household fuel choice in Zimbabwe: An empirical Test of the energy Ladder hypothesis. Resour Energy 1987;9:347–61.
[90] Masera OR, Navia J. Fuel switching or multiple cooking fuels? Understanding inter-fuel substitution patterns in rural Mexican households. Biomass Bioenergy 1997;12:347–61.
[91] Adkins E, Tyler E, Wang J, Siriri D, Modi V. Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. Energy Sustain Dev 2010;14:172–85.
[92] Bailis R, Ezzati M, Kammen DM. Greenhouse gas implications of household energy Technology in Kenya. Environ Sci Technol 2003;37:2051–9.
[93] MacCarty N, Still D, Ogle D. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy Sustain Dev 2010;14:161–71.
[94] Gebreegziabher Z, Mekonnen A, Kassie M, Köhlin G. Urban energy transition and technology adoption: The case of Tigrai, northern Ethiopia. Energy Econ 2012;34:410–8.
[95] Beyene AD, Randall AB, Gebreegzhiaber Z, Martinsson P, Mekonnen A, Vieider F. Do improved biomass cookstoves reduce fuelwood consumption and carbon emissions? Evidence from rural Ethiopia using a randomized treatment Trial with electronic monitoring. World Bank Policy Research Working Paper; 2015 7324 https://ssrn.com/abstract=2621878 Accessed 17.05.17.
[96] Helga HE. Economic evaluation of the improved household cooking stove dissemination programme in Uganda. GTZ Household energy programme-Hera; 2007http://www.un.org/esa/sustdev/csd/csd15/lc/GTZ_Uganda.pdf Accessed 15.07.17.
[97] Coelho ST, Karakezi S, Lata K. Traditional biomass; improving its use and moving

to modern energy use. Secretariat of the international conference for renewable energies. 2004. p. 21–2. Bonn, Germany.

[98] United Nations Framework - Convention on Climate Change (UNFCC). Energy-efficient Cook Stoves for Siaya Communities in Kenya. UNFCC; 2014http://unfccc.int/secretariat/momentum_for_change/items/8283.php Accessed 06.06.17.

[99] Turney D, Fthenakis V. Environmental impacts from the installation and operation of large-scale solar power plants. Renew Sustain Energy Rev 2011;15:3261–70.

[100] Tsoutsos T, Frantzeskaki N, Gekas V. Environmental impacts from the solar energy technologies. Energy Policy 2005;33:289–96.

[101] Nandwani SS. Solar cookers - cheap technology with high ecological benefits. Ecol Econ 1996;17(2):73–81.

[102] Kumar A, Kandpal TC. Potential and cost of CO2 emissions mitigation by using solar photovoltaic pumps in India. Int J Sustain Energy 2007;26:159–66.

[103] Food and Agriculture Organization of the United Nations (FAO). Charcoal production and use in Africa: What future? vol. 53. Rome, Italy: FAO; 2002. Unasylva 211.

[104] Intergovernmental Panel on Climate Change (IPCC). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC; 1996.

[105] Ministry of water, irrigation and energy of Ethiopia (MoWIE). National Biomass Energy Strategy for Ethiopia. Addis Ababa; 2014http://www.euei-pdf.org/sites/default/files/field_publication_file/Ethiopia _Biomass_Energy_Strategy_and_Action_Plan_Final_2014_02_06.pdf, Accessed date: 13 June 2017.

[106] Ministry of Energy of Kenya (MoE). Study on Kenya's Energy Demand, Supply and Policy Strategy for Households, Small scale Industries and Service Establishments. Nairobi: Kamfor Consultants; 2002. p. 133.

[107] Kaale BK. Baseline study on biomass energy conservation in Tanzania. SADC Programme for Biomass Energy Conservation (ProBEC) Report 2005:55. [Gaborone, Botswana].

[108] Wolde-Ghiorgis W. Renewable energy for rural development in Ethiopia: The case for new energy policies and institutional reform. Energy Policy 2002;30:1095–105.

[109] Ahlborg H, Hammar L. Drivers and barriers to rural electrification in Tanzania and Mozambique – grid-extension, off-grid, and renewable energy technologies. Renew Energy 2014;61:117–24.

[110] Njoroge DK. Evolution of biogas technology in South Sudan: Current and future challenges. Proceedings from bio-digester workshop. 2002http://www.mekarn.org/procbiod/kuria.htm/ Accessed 03.05.17.

[111] Githiomi JK, Mugendi DN, Kung'u JB. Analysis of household energy sources and woodfuel utilization technologies in Kiambu, Thika and Maragwa districts of Kenya. J Hortic For 2012;4(2):43–8.

[112] Mengistu MG, Simane B, Eshete G, Workneh TS. Factors affecting households' decisions in biogas technology adoption, the case of Ofla and Mecha Districts, northern Ethiopia. Renew Energy 2016;93:215–27.

[113] Yadav MP. The role of biogas for environmental sustainability in Nepal: User's perspective. J Indian Res 2014;2(3):49–56.

[114] Kamp LM, Forn EB. Ethiopia's emerging domestic biogas sector: Current status, bottlenecks and drivers. Renew Sustain Energy Rev 2016;60:475–88.

Paper II

Analysing household biogas utilization and impact in rural Ethiopia: Lessons and policy implications for sub-Saharan Africa

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Abstract

This paper analyses the current utilization rate, performance and impact of domestic biogas plants in rural Ethiopia from a case study in four districts. Data were collected from direct field investigation of 32 digesters and a survey of 605 randomly selected households. The study finds that, despite growing efforts, the dissemination and use of biogas plants in rural Ethiopia is still low. Of the total 32 biogas plants investigated, only 21 were found functional. Most of the digesters constructed are of 6m^3 capacity and the main feedstock used is cow-dung. The average quantity of biogas produced from a 6m^3 functional plant was estimated at 0.61 m^3/day. The result implies that the current level of biogas use could substitute the consumption of 631.7 kg of fuelwood and 25 litres of kerosene per household per year. However, comparative analysis of the total energy consumptions of biogas user and non-user households revealed that the effect of biogas use in reducing household fuelwood and kerosene consumption was insignificant. Given the high capital cost of biogas construction, the study suggests that a thorough revisiting of existing biogas dissemination approaches and operational practices is crucial if the technology is to make a significant contribution to the rural energy supply. In view of this, key lessons and policy implications drawn from this case study and international experiences are analysed and discussed.

Keywords: *Rural households, household biogas systems, utilization level, biogas production, biogas consumption, energy substitution.*

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1. Introduction

Lack of clean and affordable energy lies at the core of many pressing problems currently facing people in much of the developing world [1]. For the mostly off-grid households of sub-Saharan Africa, lack of access to clean and reliable energy remains a major hurdle for improving their socio-economic development, health, and environmental conditions [1-2]. Ethiopia has a large potential for renewable energy production [3]. Yet, its energy sector remains underdeveloped with low levels of access to modern energy services. According to recent data from IEA [2], biomass and bio-wastes accounted for 47.05 (91.4%) out of 51.54 MTOE (million tons of oil equivalent) of the total primary energy supply in the country in 2016 while electricity accounted for only 0.895 mtoe (1.74%). In the final energy consumption, biomass fuels accounted for 37.87 (90%) out of the 42.15 mtoe of total final energy consumed in the country in 2016 [2].

In rural areas where approx. 80% of Ethiopia's population lives in particular, access to modern and clean energy is simply unavailable; and the majority (more than 98%) of the households rely on solid biomass fuels (fuelwood, charcoal, dung-cakes and crop residue) as the primary source of energy [4-5]. This heavy reliance on solid biomass along with the rising demand for domestic energy from the rapidly growing population has exacerbated the land degradation and depletion of the country's forest resources [3, 5]. Moreover, according to WHO [6] estimates, 72, 400 Ethiopians mostly women and children die annually from diseases associated with indoor air pollution from the burning of biomass fuels and kerosene wick lamps.

Against the backdrop of this heavy reliance on woody biomass fuels and the associated negative environmental and health impacts; biogas production from anaerobic digestion of livestock manure was sought as a viable option for providing cleaner energy to rural households of Ethiopia [7 -8]. In pursuit of this, the government of Ethiopia with the support of the Netherlands Development Organization (SNV), and other international organizations launched the National Biogas Program (NBPE) in 2008 [8]. During the past decade, the NBPE has been actively supporting and facilitating the dissemination and installation of domestic biogas systems throughout the country [7-8].

Implementation of the first phase of the NBPE began in 2009 and culminated in 2013, during which 8,161 biogas plants were built in four regional states [8]. Encouraged by this modest achievement, the NBPE began implementation of the second phase in 2014. Since 2017, the Biogas Dissemination Scale-Up Program (NBPE+) is underway.

Several studies have shown that biogas systems are among the most viable options for the production of clean, cost-efficient, and environmentally sound energy with multiple benefits to user households. For instance, a study by Bedi et al. [9] in Indonesia showed that biogas users had reduced their energy-related expenditures by up to 45%. Laramee and Davis [10] in Tanzania estimated that biogas user households spent on average US$ 249 per year less on domestic energy compared with non-users. Katuwal and Bohara [11] in Nepal noted that biogas use could reduce household fuelwood consumption by up to 3 tons per year. Other studies [12 -13] have also shown that biogas use can provide substantial benefits by improving household economic and health conditions, reducing GHGs emissions, and improving crop productivity from the use of bio-slurry as fertilizer.

Despite these multiple benefits, empirical evidence suggests that the dissemination and use of biogas in much of Africa has remained low [14 - 17]. In light of this problem, most of the studies on biogas use in Africa and Ethiopia to date have focused on the adoption and dissemination of the technology, and the associated barriers [18 - 21]. However, the challenge for improving biogas use in rural Africa stems not just from the slow pace of adoption alone, but more crucially also from the lack of thorough understanding of the post-adoption course of the biogas plants, its utilization rate and impact on household energy supply. As noted by Mulinda et al. [14], one of the major setbacks for the strategic development of the African biogas sector is the lack of evidence-based analysis of long-term operational success and failure, utilization rate and impact of the biogas plants once installed and the underlying drivers. The few studies that attempted to assess the performance of biogas plants in Ethiopia so far were mostly based on data from a point-in-time field test on purposively selected fully functional digesters essentially pre-supposing that the digesters are functional at all times. As a result, very little is known about the current state of functionality, utilization rate, performance, and actual impact of biogas plants installed over the years in the country.

This lack of critical knowledge may hamper the effectiveness of the biogas program. The objective of this study was thus to investigate the current utilization rate, performance, and impacts of household biogas systems on the rural households' energy use patterns in southern Ethiopia; and draw some lessons and policy implications to improve the situation in the country and sub-Saharan Africa at large.

2. Domestic biogas use in the developing world: a brief review

Empirical evidence on domestic biogas technology adoption and use in the developing world depicts an overall picture of limited success [14-17]. On the one hand, experiences from a few Asian countries show that successful biogas use is attainable [9, 11, 12]. For instance, Bhat et al. [12] in South India found that the involvement of multiple agencies in the biogas dissemination, participation of the private sector in digesters construction, provision of subsidy, and warranting of digesters performance after installation has led to high success rates in the technology's use. Similarly, Katuwal and Bohara [11] in Nepal and Zhang et al. [22] in China noted that efficient use of biogas plants has the potential not only to provide clean energy but also reduces carbon emissions significantly.

Contrarily, other studies have shown that biogas dissemination and use in many parts of the developing world is still dismally low. According to Bond and Templeton [23], even in those Asian countries where the technology is assumed to have well developed, the rate of utilization of biogas plants is about 50%. Chang et al. [24] also reported that despite the large number of biogas plants installed in China, their utilization rate is low. In view of this, studies mostly from Asia, have noted that the success of household biogas systems is associated with a range of factors such as availability of maintenance services, government policy support, design and construction of digesters, operational skill of the users, and monitoring and follow-up of the digesters after construction [23 - 25]. Other studies have found that the low rate of adoption and utilization of household biogas systems is associated with barriers such as high cost of construction, lack of awareness, limited funding, and ineffective dissemination strategies [14 -21].

On the other hand, enabling factors positively related to the adoption and dissemination of biogas were: government subsidy and innovative financing schemes, private sector participation, high income and educational level, livestock-holding and awareness of the adopters [12, 23-25]. This evidence provides valuable insight on biogas dissemination, usage, and challenges. Yet, the success and failure of biogas technology, its utilization, and impact is highly context-specific prone to geographic and socio-economic variability [22-23]. As such, the drivers and impact of biogas use in Ethiopia entail in-depth study.

3. Methods

3.1. Study areas and sampling

This study was carried out in four rural districts of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia: Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya. Geographically, the region lies between Latitudes 4°43' - 8°58' North, and Longitudes 34°88' - 39°14' East. The SNNPRS is composed of 14 administrative zones (provinces) and 4 special *woredas* (districts), consisting of a total of 137 rural districts and 22 urban administrations. The districts are further sub-divided into *kebeles*, the smallest administrative units of Ethiopia. The total population of SNNPRS was estimated to be 19. 2 million in 2017, of which 90% were rural inhabitants composed of 2,743,502 households; and 10% were urban residents composed of 367,493 households [26].

A Multi-stage stratified random sampling approach was used to select sample districts and households. In the first stage, 23 rural districts (out of the 137 rural districts in the region); where biogas technology deployment has been actively taking place since 2008 were identified. The 23 districts were then stratified into three groups based on their agro-ecological conditions as highland, midland, and lowland. Afterwards, two districts from the highland group, one from the midland group and one from the lowland were randomly selected. Two districts were selected from the highland because more than half of the 23 intervention districts identified fell in this category. Subsequently, Aleta-wondo and Cheha districts were selected from the highland category; and Boloso-sore and Mirab-abaya from the midland and lowland strata respectively.

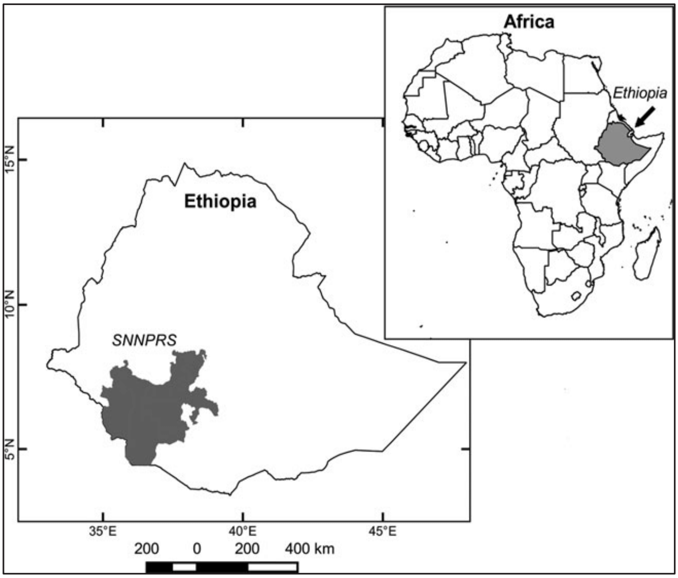

Figure 1. Map of the SNNPRS

The total estimated population of Aleta-wondo district in 2017 was 187,957 composed of 33, 738 rural households; and that of Cheha district was 122,770 made up of 24,554 households. The population of Boloso-sore district in 2017 was estimated to be 187,558 consisted of 36,410 households and that of Mirab-abaya was 90, 508 made up of 12,784 households [26]. Accordingly, in the second stage, a representative sample size for the study was determined at 95% confidence level, 4% precision (for large sample size and smaller allowable error between sample estimates and true population values) and p = 0.5 (for most conservative/largest sample size) following Cochran [27] as:

$$N = \frac{\left(z^2{}_{\alpha/2}\right)(p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\,.\,(0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:
N= is the desired sample size
P = 0.5 is the assumed population proportion expected to have access to renewables
e= 0.04 is the desired precision (or margin of error) at 4%
$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size was calculated 660. This total sample size of 660 households was then distributed to the four selected districts by using the probability proportional to the household size (PHS) method. Hence, of the total 660 samples, 207 were allotted to Aleta-wondo district, 224 to Boloso-sore, 151 to Cheha and 78 to Mirab-abaya. In the third stage, three *Kebeles* (cluster of villages) were randomly chosen from each selected district and the sample size allotted for the district was distributed to the three *kebeles* by using the PHS method. Finally, a random selection of sample households was made from a complete list of all the households in each *Kebele* using a lottery method. Random sampling of households was preferred over purposive sampling of only those households with biogas plants installed for the former allows the assessment of the actual dissemination rate of biogas plants and its effect on household energy consumption by comparing biogas users against non-users.

Table 1. Distribution of sample households by district and agro-ecology

Agro-ecology	Districts	Sample *kebeles*	Sample sizes	Sub-total
Highland	Aleta-wondo	Dengora-elmate	86	207
		Belesto	66	
		Dande	55	
Highland	Cheha	Astepo	48	151
		Megenase	60	
		Sisena-yimatye	43	
Midland	Boloso-sore	Adimencho	95	224
		Sore-homba	79	
		Achura	50	
Lowland	Mirab-abaya	Umo-lante	26	78
		Ankober	30	
		Molle	22	
	Total			660

3.2. Data sources and collection methods

3.2.1. Household survey

Cross-sectional household surveys were conducted to collect primary data by using semi-structured questionnaires. The surveys were administered through face-to-face interview with both [1]biogas adopters and non-adopters. The survey questionnaires

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[1] Biogas-adopter in this study refers to those households who have installed domestic biogas plant (whether it is currently functional or not); and non-adopter refers to those households who have not installed biogas plant at all.

were designed based on the aim of the study and review of relevant literature. Prior to the actual survey, preliminary studies were conducted in each district and information was gathered on household energy sources, types of digesters, usage and dissemination approaches and associated barriers. Afterwards, four data enumerators were hired and trained in each district on the objectives, sampling designs and data elicitation methods including ethical issues. This was followed by pretesting of the questionnaires on 24 randomly selected households from both biogas adopters and non-adopters. The pre-test results were used to enrich the survey questionnaires. Finally, the actual survey was carried out between January and December of 2018. Data gathered from the survey included: basic household characteristics, primary cooking and lighting energy sources, and consumption quantities; biogas adoption and current utilization status; installation costs; financing sources; problems faced and perspectives on solutions to the problems.

3.2.2. Direct field studies and energy consumptions measurements

To substantiate the self-reported survey data, and more accurately estimate the current utilization rate and performance of biogas plants, direct field investigations and energy consumption measurements were carried out. From the field assessments, data on the capacity of the digesters installed, the quantity of feedstock fed per day, biogas-based cooking and lighting hours per day, the quantity of bio-slurry harvested per week and total installation costs of the biogas plants were collected for all biogas adopters found during the survey. Secondly, direct measurement of household consumptions for other fuels (biomass, kerosene) was carried out to randomly selected 24 biogas adopters and 24 non-biogas adopters from the study districts for a total of two weeks.

Biogas cookstoves are much like conventional appliances that run on commercial gas-fuels. A typical domestic biogas stove in Ethiopia has a small size and single burner with multiple flame portholes and operates at atmospheric low pressure [28]. The thermal efficiency of the stoves varies from 40% -55%, and its gas consumption rate ranges from 0.25 to 0.63m^3 per hour (with an average consumption of 0.475 m3/hr) [28]. In biogas lamps, gas is burnt in lighting mantles and the glowing of the mantle causes lighting. According to the field test reports of Khandelwal and Gupta [28], the biogas lamps in Ethiopia have a luminous efficiency of 0.182- 0.191 (Lu/W) and gas consumption rate of 0.036 - 0.059 m3/hr (with an average consumption of 0.048 m3/hr). The conclusions and policy implications drawn from this study are hence primarily based on this direct field investigation of the biogas plants and survey of the sample households. Figure 2 presents pictures of a typical biogas stove and biogas lamp in use in rural Ethiopia.

Figure 2. A typical biogas stove and lamp in rural Ethiopia (Photo credit: KG.hiwot)

3.2.3. Key Informant Interview:

Individual key informant interviews were conducted with a total of 20 key informants from the four study districts. The key informants were purposively selected on the basis of their experience, role and knowledge on various aspects of the biogas program in the SNNPRS. This included 'model' biogas adopter household-heads, community-leaders, local administration officials, NBPE staff, local biogas promoters, and masons; as well as two regional level alternative energy and technology development experts.

3.2.4. Direct Matrix Score Ranking Exercise (DMR)

Following Chambers [29], Direct Matrix Score Ranking exercise (DMR) with seven focus groups involving a total of 27 participants was conducted to elicit information on the root causes of inefficient use and malfunctioning of digesters installed. To that effect, the first three DMR groups consisted of household-heads who had biogas plants installed but currently not functional. The second three DMR groups consisted of local biogas implementers and masons. The last group consisted of energy officials and experts. The DMR was conducted in two phases. By the end of the first phase, an exhaustive list of causes for biogas malfunctioning and failure were identified by the participants. In the second phase, each group was asked to rank the causes of malfunctioning and inefficient use of the biogas plants out of 5, where 5 = most important and 1 = least important.

3.2.5. Track-record data and secondary sources:

In addition to the primary data collected through the above methods, official data on the number and capacity of digesters installed in the four districts between 2011 and 2017, and track-record and inventory reports on their current (2018) operational status was obtained from the district energy offices. Moreover, reports from the NBPE/SNV, and international experiences, published and unpublished research outputs related to the biogas sector in Asia and Africa were consulted to supplement the case study.

3.3. Data analysis

3.3.1. Descriptive and inferential statistics

Descriptive statistics and cross-tabulations were used to analyse the characteristics of sample households, recent biogas dissemination trends, and current operation status. An independent samples [2]Welch's T-test, Pearson’s chi-square ($\chi2$) test and multiple linear regression analysis were employed to determine the significance of differences in mean values of explanatory variables between [3]biogas users and [4]non-users as well as to examine the effect of biogas use on households’ fuelwood consumptions.

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[2] The student’s t-test is commonly used to compare the means of two independent samples (groups) with equal variances; however the Welch’s t-test is more robust and reliable when the two samples have unequal variances and/or the sample sizes are unequal.

[3] Biogas user in this study refers to those households who have adopted (installed) biogas plant and are currently using biogas energy for cooking, lighting or both.

[4] Biogas non-user in this study refers to those households who have not adopted (installed) biogas plant at all, plus those who have adopted biogas but it is not currently functional.

3.3.2. Daily biogas production and consumption analysis

Based on the quantitative data collected from the field studies, the average quantity of cow-dung fed to the digesters per day, average biogas-based cooking and lighting hours per day, and average bio-slurry harvested per week were calculated. Using these results in conjunction with the average gas consumption rate of typical biogas cookstoves and biogas lamps in Ethiopia from previous tests [28]; the average daily biogas production and consumption per household per operational plant were estimated by applying the method suggested by IRENA [30, p. 14]. It is assumed that estimating the daily biogas use of households based on the daily biogas-based cooking and lighting hours and gas consumption rates of the appliances can provide a more accurate estimate of the actual biogas use of rural households compared to gas-flow measurement methods especially in the face of problems such as gas-leakage, and clogging of pipelines and the challenges associated with accurate metering of gas flow under low pressure, varying composition of the gas, and high moisture content [30].

4. Results and Discussions

4.1. Profiles of biogas adopters and non-adopters

Of the total 660 sample households determined for the study, 605 completed the survey. The data collected from the remainder 55 were either incomplete or highly inaccurate when cross-validated and hence excluded. The overall response rate was thus 91.7%. Almost in all cases, the respondents were household-heads. As the summary statistics in Table 2 show, of the 605 households that completed the survey, 31% (189) were from Aleta-wondo district, 34% (204) were from Boloso-sore, 22% (134) were from Cheha while 13% (78) were from Mirab-abaya. In terms of gender, 84.13% (509) of the sample households are headed by males and the remainder 15.87% (96) by females. Contrary to our expectations, only 32 households from a total of 605 effective samples had adopted (installed) the biogas technology. Although a more robust study covering all the districts of the SNNPRS may be needed to accurately estimate the overall adoption rate, the above results suggest that the current rate of uptake of domestic biogas plants in the four districts is not more than 5.3%. This supports the findings of previous studies that reported low adoption and dissemination rate of domestic biogas technology in Ethiopia and sub-Saharan Africa [14-17]

Table 2. Demographic and socio-economic profiles of biogas adopters and non-adopters

Variables		Stat	Biogas-adopters (N=32)	Non-adopters (N=573)	Total samples (N = 605)	SE
Location/district	Aleta-wondo		12	177	189	
	Boloso-sore		8	196	204	
	Cheha		7	127	134	
	Mirab-abaya		5	73	78	
Gender of HH head	Male	Freq.	29	480	509	
	Female	Freq.	3	93	96	
Age of HH Head		Mean	46.40	49.03	48.30**	10.92
Educational status		Mean	8.68	4.70	4.73***	3.77
Household size	< 15 years	Mean	4.00	2.74	2.80***	1.83
	Total HH size	Mean	7.32	6.20	6.24**	2.38
Total landholding size in ha		Mean	1.12	0.66	0.70***	0.64
Cattle heads-size		Mean	4.52	2.72	3.50**	2.36
Main occupation of the household	Cash cropping	%	50.10	31.00	32.00	
	Food cropping	%	10.00	27.00	26.00	
	Crop-livestock mixed farming	%	32.50	23.50	24.00	
	Off-farm activity	%	0.00	13.80	13.00	
	Small business	%	8.00	4.80	5.00	
Gross average annual cash income/HH in Ethiopian Birr (ETB)		Mean	61406	22 009	22 155***	22350
Access to credit service		%	62.50	34.03	35.04	
Grid electricity connection		%	34.38	31.94	32.06	
Round-trip walking distance to forest (wood source) in minutes		Mean	74.60	61.20	62.40**	75.20

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

In line with the findings of an earlier study by Mengistu et al., [15] in Northern Ethiopia, most (90.6%) of the biogas adopters were male-headed households. This might be due to the effect of gender-related socio-cultural and economic factors (inequalities) such as income, landholding size, labour availability, and cattle-heads size on biogas adoption. However, the results of the Chi-square ($\chi 2$) test for independence (Table 3) showed that biogas adoption is not significantly associated with the gender of the household-head.

Consistent with earlier studies in Kenya and Ethiopia [20, 22], the average age of biogas adopter household-heads (46.40) is significantly lower than the non-adopters (49.03). Concerning educational status, measured in terms of the number of years of schooling completed, biogas-adopters (8.68) were found to have significantly higher educational level compared to non-adopters (4.70). This supports the notion that educational status and awareness significantly affect biogas adoption decisions of households. Compared to the non-biogas adopters (6.20), the average family size of biogas adopters (7.32) was significantly higher. Similarly, the number of family members under the age of 15 was sizably higher for biogas adopters (4.0) than the non-adopters (2.74). This substantiates the accounts of some non-biogas adopters that the high labour demand of biogas operation was one of the reasons they avoided adopting it.

Both the mean landholding size (1.12 ha) and cattle heads size (4.52) of biogas adopters were significantly higher than the landholdings (0.66 ha) and cattle heads (2.72) of non-adopters. This supports previous studies that reported landholding and cattle heads size are among the main factors positively influencing households' adoption of biogas [20 - 22]. Landholding size influences biogas adoption both directly by determining the land available for installing the digester, and indirectly by affecting the household's income. The mean annual gross cash income of biogas adopters (ETB 61, 406 ≈ US$ 2270) was significantly higher than the non-adopters (ETB 22, 009 ≈ $810). Manifestly, household income is one of the foremost determinants of biogas adoption documented by several previous studies [20-23]. It was also clear from the Chi-square analysis results in Table 3 and the household income distribution in Figure 3, that household biogas ownership is strongly influenced by the household's income level.

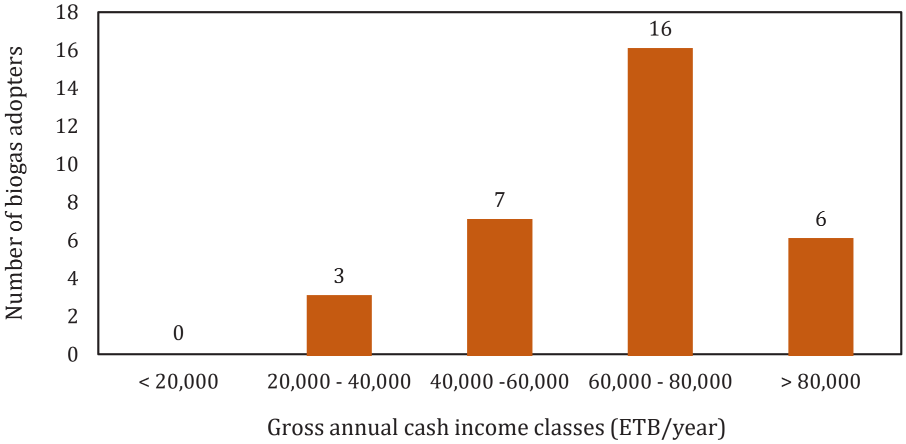

Figure 3. Biogas adoption patterns by gross annual cash income of households

None of the sampled households with annual gross cash income below ETB 20,000 had adopted biogas plants whereas households with average annual gross cash income of ETB 60,000 and above (≥ US$ 2200) constituted 68.75% of the total biogas adopters. The disparity in household income level is also mirrored in the notable difference in the percentage of households engaged in cash-crops growing (coffee, banana, and khat) as their main occupation between biogas adopters (50%) and non-adopters (31%). Access to credit financing services is higher for biogas adopters (62.5%) compared with non-adopters 34.0%. The Chi-square test results in Table 3 also indicate that ownership of biogas plants is strongly associated with access to credit service. This strengthens the assertion that access to credit finance improves the adoption of biogas by reducing the burden from high upfront costs required for installing the technology.

Table 3. Pearson's Chi-square (χ2) test for association between biogas adoption and some of the categorical explanatory variables

Variable		n	Biogas adoption		χ2 stat	P-value
			Adopters	Non-adopters		
Gender	Male	509	29	480	1.066	0.301
	Female	96	3	93		
Gross annual cash income class (ETB)	< 20,000	268	0	268	74.747***	0.000
	20,000 –40,000	123	3	120		
	40,000 –60,000	108	7	101		
	60,000 – 80,000	66	16	50		
	> 80,000	40	6	34		
Location (district)	Aleta wondo	189	12	177	1.382	0.709
	Boloso-sore	204	8	196		
	Cheha	134	7	127		
	Mirab-abaya	78	5	73		
Access to credit service	Yes	212	20	192	11.191***	0.000
	No	393	12	381		
Grid connection	Yes	194	11	183		
	No	411	21	390	0.082	0.773

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

The percentage of households connected to the grid is slightly higher for biogas adopters 34.38% than the non-adopters 31.94%. This might be because biogas adopters are often financially well-off compared to the non-adopters; as such, they could afford electricity connection that usually costs the household about ETB 5,000 for the electric meter and connection lining alone. However, the Chi-square analysis result in Table 3 showed that biogas adoption is not statistically significantly associated with grid connection. The average round-trip walking distance between the households' home and main fuelwood sources (usually state and communal forests and woodlands) is significantly longer for biogas adopters than the non-adopters (see Table 2). In terms of location, however, the Chi-square test results indicated that biogas adoption is not statistically significantly related to the location (district) of the household despite a relatively higher number of biogas plants are constructed in Aleta-wondo district.

4.2. Energy sources of biogas adopters and non-adopters

From the analysis of primary energy sources of sample households (Table 4), we found that the vast majority (about 97%) of the survey households depend on solid biomass fuels (fuelwood, charcoal, agri-residues and animal dung cakes) for cooking and heating. Fuelwood, in particular, stands out as the main cooking fuel for almost 91% of the total households surveyed. Comparison of biogas adopters and non-adopters with respect to the primary cooking fuel (Table 4) shows that 46.88 % of biogas adopters and 93% of non-adopters depend on fuelwood as their main cooking fuel.

Table 4. Primary energy sources of biogas adopters and non-adopters for cooking and lighting

Variables		Stat	Biogas-adopters (N=32)	Non- adopters (N=573)	Total samples (N = 605)
Main energy sources for cooking and heating	Fuelwood	%	46.88	93.19	90.74
	Agri-residues	%	3.13	3.14	3.14
	Charcoal	%	12.50	1.75	2.31
	Biogas	%	37.50	0.00	1.98
	Grid electricity	%	0.00	1.22	1.16
	Dung-cakes	%	0.00	0.70	0.66
Main energy sources for lighting	Kerosene	%	25.00	51.48	50.08
	Grid electricity	%	34.38	28.62	28.93
	Solar	%	3.13	19.90	19.01
	Biogas	%	37.50	0.00	1.98

Surprisingly, only 37.5% of the biogas adopters reported biogas as their main cooking fuel. As will be discussed later in this paper, the main reason why more than 62% of the biogas adopters are not deriving their primary cooking fuel from biogas relates to the poor performance and malfunctioning of many of the biogas plants constructed. On the other hand, agri-residues and charcoal remain important cooking fuels for both groups reported by 3.14%, and 2.31% of the total households respectively. In what appears to be a new step, grid electricity has emerged as the primary cooking fuel for about 1.16% of the sample households compared to almost 0% in the past [26]. Concerning lighting energy however, the figures in Table 4 indicate that overall about 50% of the sampled households rely on kerosene as primary energy sources for lighting.

Compared to the 70-80% kerosene dependency of rural households in the SNNPRS as primary lighting fuel in 2010 [26], the present figure may indicate a decreasing trend in kerosene-based lighting following Ethiopia's recent progress in rural electrification and solar photovoltaics (PV) dissemination. This is also evidenced by the results in Table 4 where 28.62% and 19.90% of non-biogas adopters reported grid electricity and solar as their primary energy sources for lighting respectively. By contrast, only 37.5% of biogas adopters use biogas as the main energy source for lighting; while 25% and 34.4% of the same biogas adopters rely on kerosene and electricity respectively for lighting. Despite the significant percentage of households that reported electricity and solar as primary lighting energy sources however, the energy consumption analysis showed that many of the households do consume a non-negligible amount of kerosene, candles and/or dry-cell batteries as complementary and back-up lighting fuels to meet their basic lighting energy requirements. This is largely due to the unreliability of the grid electricity supply and limited capacity of the solar PV systems and lanterns; besides the poor performance and the limited energy output from many of the biogas plants.

4.3. Dissemination trends and current utilization status of biogas plants

4.3.1. Recent dissemination trends of biogas in Ethiopia

According to the data reported by SNV and the African Biogas Program/Ethiopia [7, 31], by the end of the first phase of implementation of the Ethiopian biogas program (NBPE) which lasted from 2009 to 2013, about 8,161 biogas plants were built in four selected regions of the country out of the 14 000 digesters initially planned. In the second phase, which lasted from 2014 to 2017, the construction of an additional 20, 000 digesters was planned; and a total of 12,071 digesters were installed in the country. This makes the total number of biogas plants constructed in the country between 2009 and 2017 about 20, 232 against a plan of 34,000 (close to 60% of the digesters planned). These figures illustrate that the dissemination of biogas plants in Ethiopia over the last decade has increased but not as expected. More so, only 32 households from a total of 605 samples were found to have adopted biogas technology in this study as noted earlier.

To further understand the temporal trend of biogas dissemination in the study areas, we analysed the official track-record data (see Appendix I) on the type and number of digesters installed in the four districts between 2011 and 2017 as shown in Figure 4.

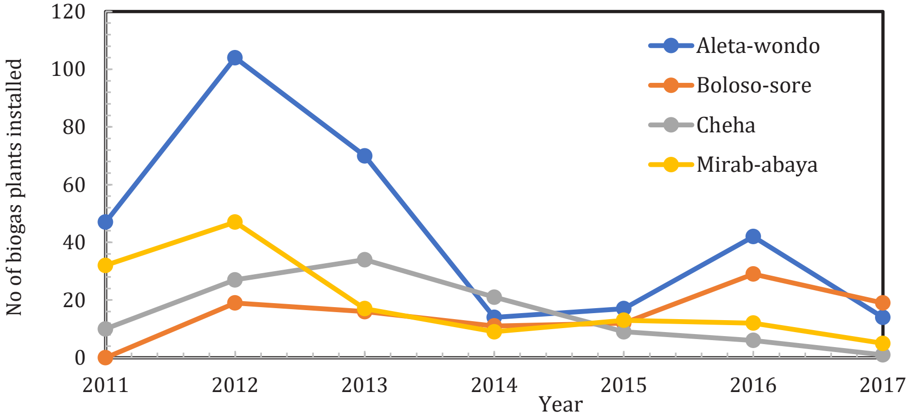

Figure 4. Biogas dissemination trends between 2011 and 2017 in the study areas

Based on the official track-record data, between 2011 and 2017, a total of 657 digesters had been constructed in the four districts. From the total 89 biogas plants installed in 2011, nearly half of them were in Aleta-wondo. In 2012, the number of digesters installed in the four districts had more than doubled (197). However, a closer look at the data shows that in 2013 and the two years that followed, the construction of digesters had plummeted in most of the districts. According to the key informants and household-heads interviewed, the drastic decline in the number of new adopters in 2014 and 2015 was largely due to the severe drought that hit much of the country and led to the loss of significant cattle population. However, they underscored that the overall decline in the uptake of biogas plants over the years is attributable to the negative spill-over effects of dissatisfied adopters from the failure of many of the digesters constructed.

The majority of the biogas plants installed are the fixed dome model, adaptation of the Nepalese GGC-2047 model. And about 89.5% (588) of them have a 6m^3 capacity, while 10.5% (69) have 8m^3 digester capacity. The main motivation for the preference of 6m^3 digesters over other sizes is perhaps due to its compatibility with the average household size, cattle head sizes, ease of operation, and low cost compared to its size [32].

4.3.2. Current utilization rate of the biogas plants installed

One of the aims of this study was to investigate the current utilization status of biogas plants installed over the years in the study districts. According to our results, out of the 32 biogas plants examined during the field study, only 21 (65.6%) were fully or partially functional in 2018; while the remaining 11 (34.4%) were non-functional or have failed beyond repair. Partially functional in this context refers to the operation of biogas plants either for lighting or cooking or bio-slurry purpose only. In light of our findings from the field examination, we analysed the current operational status of the 657 biogas plants constructed in the study districts since 2011 based on field inventory reports of each district as presented in Appendix I and summarized in Table 5.

Table 5: Current (2018) operational status of biogas plants installed between 2011-2017

District	6m^3		8m^3		Total operat.	Total non-operat.	Total installed	% Operati.
	Operat	Non-operat.	Operat	Non-operat.				
Aleta-wondo	142	160	3	3	145	163	308	47.1
Boloso-sore	63	37	4	2	67	39	106	63.2
Cheha	29	33	15	31	44	64	108	40.7
Mirab-abaya	73	51	8	3	81	54	135	60.0
Total	307	281	30	39	337	320	657	51.29

The result shows that of the 308 digesters constructed in Aleta-wondo district between 2011 and 2017; only 145 (47%) were functional in 2018. In Boloso-sore district, out of the 106 digesters constructed during the same period, 67 (63.2%) were functional. In Cheha district, only 44 (40.7%) of the 108 biogas plants installed during the same period were operational. Of the total 135 biogas plants installed in Mirab-abaya, 81 (60%) were operational. This means out of the total 657 biogas plants installed between 2011 and 2017, only 51.3% (337) were functional; and the remaining 48.7% have malfunctioned.

The above results generally concur with the findings of Bond and Templeton [25] who reported that the rate of functionality biogas plants in many Asian countries is not more than 50%. The rate of functionality of 6m^3 digesters was found to be relatively higher (52.2%) than 8m^3 digesters (43.5%) perhaps because the former is more suitable to the feedstock and labour availability of rural households in Ethiopia to maintain the regular operation of the plants than the later.

4.4. Biogas production and consumption from functional digesters

In light of the current functionality rate of the digesters discussed above, we estimated the average quantity of biogas produced and consumed per day per operational plant based on the data collected from the 21 functional plants. From the analysis of the data, it was found that the average quantity of cow-dung fed to a 6m^3 digester per day was 22.5 kg; instead of feeding 40 - 60 kg to produce the daily biogas required for an average household of 5 persons in rural Ethiopia [32-33]. The reasons for the underfeeding of digesters, according to biogas users, were a shortage of feedstock and labour to collect the manure and feed the digesters. The average biogas-based cooking hours per day was calculated 1.05 hours, and the average biogas-lamp lighting hours per day is 2.30 hours. From previous test results by a consortium of institutes from eight developing countries including Ethiopia [28], the average gas consumption rate of a typical biogas stove in Ethiopia was estimated at 0.475 m3/hr and the gas consumption rate of a typical biogas lamp was 0.048 m3/hr [28]. By using these results, and the method suggested by IRENA [30], the average daily biogas consumption for cooking and lighting per user household was calculated as shown in Tables 6 and 7.

From the results, the average daily biogas consumption of a biogas user household for cooking was about 0.50 m^3; which equates to 15m^3/month and 182 m^3/year. Assuming the effective heat content of 1 m^3 of biogas is equivalent to 3.47 kg of fuelwood [33-34], the estimated annual biogas use of 182 m^3 for cooking could substitute the consumption of an estimated 631.7 kg of fuelwood per user household per year. This translates to an average fuelwood saving of 90 kg per capita per year for cooking. However, as will be seen in the next section, this potential fuelwood saving from biogas use is not more than 10.7 % of the total fuelwood consumption of the household.

Table 6. Estimation of biogas consumption for cooking and heating

Measurements (computations)	**Results**	**Data sources**
Digester capacity of the biogas plants studied	6m^3	Own field studies
Average daily biogas production capacity of a 6m^3 fixed dome digester in developing countries	1.6 – 2.4 m^3/day	Eshete et al. [32] Schwarz [33]
Quantity of cow-dung needed to produce the average daily biogas requirement (1.6 -2.4 m^3) per day	40 – 60 kg/day	Eshete et al. [32] Schwarz [33]
Average quantity of cow-dung currently fed to the digesters/day in kg (measured in the study areas)	22. 50 kg/day	Own measurement (2018)
Average biogas-based cooking hours/day per HH	1.05 hrs/day	Own data (2018)
Gas consumption rate of typical (small-sized) biogas burner (stove) in Ethiopia from previous tests	0.475 m^3/hr	Khandelwal and Gupta [28]
Estimated biogas consumption for cooking/day	= 1.05 hrs * 0.475 m^3/hr = 0.50 m^3/day	
Estimated biogas consumption for cooking/year	= 0.50 m^3/day * 365 ≈ 182 m^3/year	
Fuelwood equivalent of biogas consumed for cooking per year (1m^3 biogas ≈ 3.47 kg of fuelwood) [34]	= (182 m^3) * 3.47 kg/m^3 = 631.7 kg	

In terms of lighting energy, our estimates in Table 7 show that the average daily biogas consumption of a biogas user household for lighting was about 0.110 m^3; which equates to 3.30 m^3/month and 40.15 m^3/year. Assuming the heat content of 1 m^3 of biogas is equivalent to 0.62 L of kerosene [34], this annual biogas use of 40.15 m^3 for lighting translates to a potential substitution of 25 L of kerosene per year.

Table 7. Estimation of biogas consumption for lighting and total biogas use per day

Estimated average biogas-lighting hours/HH/ day	2.30 hrs	Own survey (2018)
Biogas lamps gas consumption rate in m^3/hr	0.048 m^3/hr	[28]
Estimated biogas consumed for lighting/HH/day	= 2.30 hrs * 0.048 m^3/hr = 0.110 m^3/day	
Estimated biogas consumed for lighting/HH/year	= 0.110 m^3/day * 365 = 40.15 m^3/year	
Kerosene equivalent of biogas consumed for lighting per year (1 m^3 biogas ≈ 0.62L of kerosene) [34]	= (40.15 m^3) * 0.62 L/m^3 = 25. 0 L	
Total biogas consumption/HH/day	= 0.50 m^3 + 0.11 m^3 = 0.61 m^3/day	
Total biogas consumption/HH/year	= 0.61m^3 * 365 = 222.65 m^3/year	
Current production efficiency of the biogas plants compared to their production capacity	= (0.61m^3 /1.6 m^3 to 0.61m^3/2.4 m^3) = 25% - 38%	

Indeed, this is a considerable amount of lighting energy substitution from biogas use. Yet, as will be shown by the comparative fuel consumption analyses in the next section, this biogas use for lighting has not reduced the total annual kerosene consumption of biogas users significantly compared to non-biogas users. Since all the domestic biogas plants installed in the study areas and rural Ethiopia at large have only one burner and one lamp, the total biogas consumption per day can be estimated by simply adding the biogas consumed for cooking and lighting (0.5 m^3 + 0.11 m^3), which equals to 0.61 m^3; i.e. roughly 222.65 m^3/year. From the field studies, it was confirmed that all the biogas produced is consumed within 24 hours; implying that the daily biogas production rate is essentially the same as the daily consumption. In this regard, biogas users explained that because the biogas produced is insufficient, they usually use the biogas to cook only one or two family-meals per day to avoid running out of gas for lighting.

Comparing our estimate of average biogas production of 0.61 m^3/day with an average biogas production of 2 m^3/day estimated by Ghimire [13] from 4 m^3 to 15 m^3 fixed-dome digesters under the same SNV program highlights that the performance and biogas output of digesters in the study areas is rather very low. Along the same lines, compared to the daily average biogas production capacity of a 6m^3 digester estimated to be 1.6 - 2.4 m^3 in the context of sub-Saharan Africa [32-33]; our current estimate of 0.61 m^3 daily biogas production suggests that the current production efficiency of the biogas plants in the study districts is roughly between 25% and 38% of their production capacity. These results corroborate that the challenge for improving biogas use in Ethiopia is not only from the low rate of adoption of the technology but more importantly, is also from the malfunctioning of the digesters already installed and the very low production efficiency and limited biogas output of those plants that are functional.

Despite the limited volume of biogas produced, however, some biogas users were highly motivated and determined to use the technology regularly on the grounds of the benefits they obtain from using the bio-slurry (digestate) as organic fertilizer. From our analysis of the field measurements, it was found that a biogas user household on average collects 44.15 kg of bio-slurry per week from a functional plant. According to the biogas users, this bio-slurry harvested from biogas production could enable them to substitute the application of at least 50 kg of chemical fertilizers per year, which is equivalent to saving

ETB 725 (US$ 27) per annum. However, the main reason for using the bio-slurry, more than the monetary gains from replacing chemical fertilizers, was that it is highly suitable for growing ‘Enset’ (*E. ventricosum*), a staple food crop in much of southern Ethiopia, and to lesser extent for banana plantations.

4.5. Impact of biogas use on household energy consumption patterns

To examine the effect of biogas use on household fuel consumption, we analysed the data collected from the direct energy consumption measurements and the surveys. The results (see Table 8) indicate that the average fuelwood consumption of biogas user and non-user households were about 4665 kg and 5225 kg per year respectively. And the difference in mean annual fuelwood consumption between the two groups is 560 kg per year. This means that biogas user households could save 10.7% (560 kg) of their annual fuelwood consumption as a result of the biogas use. However, the impact of this energy substitution on the household’s total fuelwood consumption is found to be insignificant. This supports our earlier finding from the daily biogas use estimates that biogas user households could save on average 631.7 kg of fuelwood per year from biogas energy use for cooking. Assuming that 50% of the 20, 232 total number of biogas plants constructed in Ethiopia until 2017 are functional, the findings from this study suggest that Ethiopia could substitute 9.4% (5.66 Mt) of its total biomass consumption for domestic energy use that was estimated to be 60 Mt/year.

Table 8. Average household energy consumptions between biogas users and non-users per year

Variables	Biogas-users (N=21)	Non- users (N=584)	Total Mean (SE) (N = 605)	P- value
Fuelwood consumption/year, kg	4665.2	5225.4	5021.8 (2692)	0.0516
Charcoal consumption/year, kg	55.55	74.8	73.33 (103)	0.0505
Agri residue consumption/year, kg	495.45	534.03	532.46 (412)	0.1180
Dung-cakes consumption/year, kg	7.00	17.53	17.45 (36.13)	0.0911
Kerosene consumption/year, Lit	22.50	30.50	30.09 (38.95)	0.2622
Grid-electricity expenditure/yr, ETB	90.19	111.28	109.92 (199)	0.0960

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

Comparison of the mean consumption quantities for other fuels between the two groups showed that biogas-users consume about 38.6 kg of agri residues, 19.25 kg of charcoal, 10.53 kg of dung-cakes and 8.0 L of kerosene less per year as well as spend ETB 21.09 for electricity less per year than non-users. Yet, the differences in energy consumption quantities and expenditures between the two groups are again insignificant for all these fuels. This suggests that, while biogas use may have reduced household woody biomass and kerosene consumptions by a certain amount, its overall impact in curbing the heavy dependence on solid biomass fuels and kerosene oil remains insignificant.

In stark contrast to our results, Subedi [35] and, Somanathan and Bluffstone [36] in Nepal estimated that biogas use from a 6m^3 digester could reduce household fuelwood consumption by up to 3000 kg and by 1240 -1290 kg per year respectively. The findings of Subedi [35] show that biogas users could reduce their kerosene consumption by 38 L per year. A study by Bedi et al. [37] in Rwanda found that biogas user households were able to reduce their fuelwood consumptions by 34% per year. Comparing the findings from these studies with the results in this study highlights that the performance and effect of biogas plants in reducing household fuelwood dependence and inducing energy transition to clean sources in rural Ethiopia is yet very limited.

There are two main reasons for the limited impact of biogas in the study areas and rural Ethiopia at large. The first is that the utilization rate of biogas plants is very low, and the biogas produced from functional digesters is nearly one-third of the production capacity of the digesters. As a result, the biogas consumed by the household per day is insufficient to induce substantive cooking and lighting energy substitution. A related problem is that, in some cases, even when there is biogas produced, biogas owners were not able to use it because the biogas burner is corroded, or the lamp is broken. The second reason could be that the energy demand of biogas users was never met in the first place, the access to biogas might have created a new opportunity to increase their total energy consumptions while maintaining the use of traditional fuels little changed. This was evident from the fact that the difference in mean kerosene consumption between biogas users 22.5 L and non-users 30.50 L was only 8.0 L despite the considerable lighting energy use (25 L kerosene equivalent) from biogas.

To further analyse the effects of biogas on household energy use, we fitted a multiple linear regression model such that the total annual household fuelwood consumption is the dependent variable (Y_i) against some predictors. The result (Table 9) indicated that the average difference in the predicted value of Y (total fuelwood consumption kg/year) between biogas non-users ($X_1 = 0$) and users ($X_1 = 1$) is -698.23 ± 238.87 with P-value =

0.113. This confirms that the fuelwood consumption of biogas users is indeed lower than non-users (the reference group). Yet, the energy substitution effect of biogas use is not large enough to induce a significant change in the households' fuelwood consumption.

Table 9. Results of multiple regression of fuelwood consumption of survey households

Regression Statistics	
Multiple R	0.5713
R Square	0.3221
Adjusted R Sq.	0.3035
Standard Error	191.23
Observations	605

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	9.5E+06	8631995	11.918	9.48E-8
Residual	594	3.32E+07	724276		
Total	604	4.27E+07			

	Coefficients	*SE*	*t-Stat*	*P-value*	*Low 95%*	*Upp 95%*
Intercept	775.70	238.85	6.05***	0.0000	307.55	1243.85
Biogas use (user)	−698.23	328.87	−1.58	0.1131	−1342.82	−53.64
Gender (female)	151.75	46.73	2.04**	0.0430	60.16	243.34
Grid connection	−101.52	78.54	−1.94	0.0564	−255.46	52.42
Location (Boloso)	−144.25	85.73	−0.33	0.7691	−312.28	23.78
Location (Cheha)	−179.71	109.3	−2.23**	0.0311	−393.94	34.52
Location (Mirab)	−232.23	101.81	−4.49***	0.0042	−431.78	−32.68
Age of HH head	13.43	11.36	1.18	0.2378	−8.84	35.70
Household size	359.29	56.29	6.38***	0.0000	248.96	469.62
Gross income /yr	−261.03	100.005	−2.63**	0.0301	−457.04	−65.02
Distance to forest	−318.65	67.01	−3.26***	0.0011	−449.99	−187.31

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.
Location: Aleta-wondo is the reference category

The results in Table 9 also reveal that gender (female) and family size of the household are positively and significantly associated with households' fuelwood consumption. This means that female-headed households and households with larger family sizes consume a higher quantity of fuelwood per year than those that are headed by males and with fewer family size. Conversely, an increase in income and distance to forest (wood source) of the household are negatively and significantly associated with fuelwood consumption. The coefficients for the variable location indicate that, compared to Aleta-wondo district (the reference category), household fuelwood consumption is significantly lower in Cheha and Mirab-abaya districts at $p < 0.05$ and $p < 0.01$ respectively.

4.6. Causes of malfunctioning and inefficient use of biogas plants

Given the high rate of malfunctioning and failure of biogas plants studied, some within a short period of installation, and the poor performance of those that are functional; the critical questions were: why have so many of the biogas plants failed? What made biogas adopters to dis-adopt and abandon the use of the plant they spent a lot to build? What is impeding the efficient use of biogas? To address these questions and understand the root causes of the problem, we conducted Direct Matrix Score Ranking (DMR) exercises and the calculated cumulative score values are presented in Figure 5

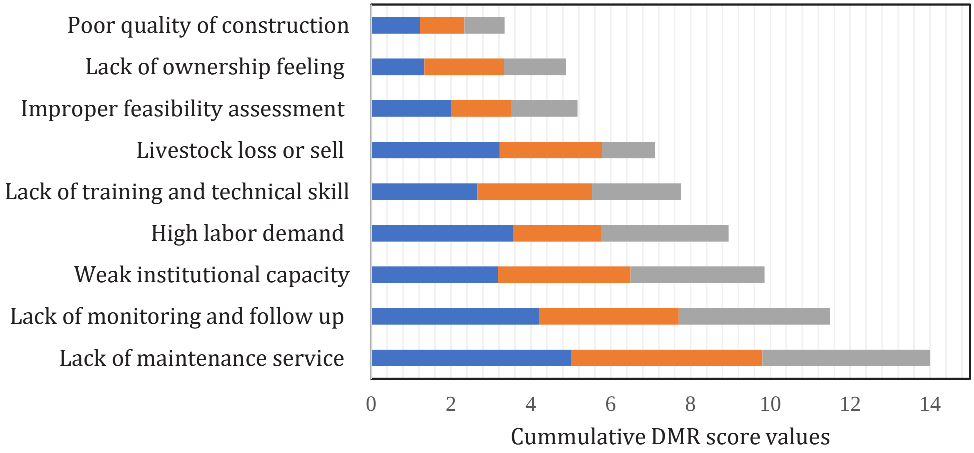

Figure 5. Cumulative average score values of reasons identified for biogas failure

4.6.1. Lack of maintenance services and spare parts

One of the critical conditions for effective use of biogas systems is ensuring that adopters utilize the technology regularly once installed. In this respect, the results of the DMR analysis revealed that lack of timely maintenance services and spare parts was one of the principal factors for the failure of many of the biogas plants installed. According to the DMR participants, faults in the biogas system often arise from leakage of gas pipes, defective or corroded valves, inoperative stoves and lamps, breakdown of the anaerobic digestion process in a short period, and blockage in the bio-slurry disposal system.

This lack of maintenance services is exacerbated by the general lack of maintenance centres and qualified biogas technicians and lack of spare parts in the domestic market. Several other studies have also reported that lack of maintenance and repair is one of the main reasons for the failure and inefficient use of biogas plants in many developing countries [15, 23-25].

4.6.2. Lack of monitoring and follow up from the NBPE/installer side

Under the current situation of biogas implementation in rural Ethiopia, monitoring and follow-up of operation and management of biogas plants, supervision of the quality of digesters construction; and technical assistance on problems faced by users are rarely done by the biogas implementing body (NBPE) if at all. A large part of the problem is tied to budget and human resource constraints. In line with the statements of the DMR participants, Osei-Marfo et al., [19] explained that the lack of monitoring and follow-up was one of the major setbacks for widespread and efficient use of biogas in Ghana.

4.6.3. Lack of well-defined policy frameworks and weak institutional capacity

Albeit the high-level political commitment of the Ethiopian government for renewable and clean energy access; biogas as an energy sector still lacks sound and enabling policy and institutional frameworks. The most relevant policy directives concerning biogas in Ethiopia to date are a handful of policy instruments stated in the National Energy Policy which read as: "strengthening and promoting market-based private sector participation in biogas development; as well as promoting the construction and effective use of bio-digesters" [3, p. 37]. Besides the inadequacy of these policy instruments, there are no specific guidelines and regulations formulated to implement these policy instruments. Furthermore, the institutional structure of the biogas program at the district level is utterly weak and mere subordinate to the ‘District Water, Mines, and Energy Office’ [21]. From there implementation of the biogas program rests on the shoulders of one focal person and two to three personnel, who at the same time, are also responsible for the implementation of all other energy-related programs including improved cook-stoves and solar technologies to about 33,000 households in each district. This has created a severely understaffed and under-resourced biogas implementing unit unable to conduct even the smallest demonstration or training activities to users and potential adopters.

4.6.4. High labour demand and competition from other farm activities

Labour is a crucial factor of production in rural Ethiopia and labour allocation decision of a household considers several factors including the return from the activity, available workforce, and market for the product. Findings of the DMR analysis showed that the high labour demand for biogas operation and the stiff competition for labour from other farming activities was one of the main reasons ranked for the irregular operation and malfunctioning of digesters installed. According to the participants, households often give priority to farm activities that either ensure household food security or provide lucrative returns such as coffee, khat, and banana production. As a result, the labour allocated to biogas operation and management will be small leading to inadequate and irregular feeding of the digesters and subsequent failure of the biogas plants.

Contrary to the general understanding that biogas use saves a substantial amount of rural households' time and labour, a study by DFID [38] in selected sub-Saharan African countries indicated otherwise. According to this study, the average savings in time spent collecting fuelwood by biogas user households was about 2.58 hours per week. On the other hand, the average time needed to collect water for the digesters was estimated at 1.53 hours per week. When the time spent for collecting water is accounted for together with the labour required to collect and mix the feedstock and feed the digesters (6.47 hours/week), the total household labour increases by an average of 5.42 hours per week as a result of the biogas operation.

4.6.5. Lack of post-adoption training and operational knowledge/skills

Lack of proper post-adoption training and poor operational practice by biogas adopters was another major hurdle identified for the underutilization of biogas plants. According to the participants, the lack of basic training and gap in biogas operational knowledge has led to poor operational practices of the digesters and inefficient production of biogas thus eroding the satisfaction and ownership feeling of the users. In this regard, it was found that of the total 32 biogas owners surveyed, only 10 (31.25%) had received basic training on how to operate the plant while the remaining 22 (68.75%) have not, but have taken part in a simple orientation gathering or a short field demonstration.

In accord with our findings, Mengistu et al. [21, p. 126] in Northern Ethiopia, wrote that "with the exception of provision of simple orientation or instruction for a few minutes by masons and/or supervisors, biogas user training was neither given uniformly across all biogas implementing regions; nor to all biogas user households". Along the same lines, assessing the problems of biogas systems in sub-Saharan Africa, Mulinda et al. [14] and Parawira [16] noted that lack of adequate training and skill on proper operation of the digesters was one of the key factors for the subsequent abandonment of biogas plants.

4.6.6. Livestock loss or sell and subsequent shortage of feedstock/cow-dung

The main feedstock for biogas production in rural Ethiopia is cattle manure. As such, any change in the household cattle holding size will affect biogas production. From the DMR exercises and key informant discussions, it was evident that one of the main reasons for the abandonment of biogas plants particularly in the lowland district of Mirab-abaya (traditionally a cattle-herding district) was the loss of cattle population and subsequent shortage of cattle manure due to a deadly livestock disease that prevailed in the area for some time. In the case of Aleta- wondo and Boloso-sore districts, some biogas adopters sold some or all of their cattle holdings for economic reasons, which resulted in shortage of feedstock (cow-dung) and insufficient feeding or shut-down of the digesters. From a strategic biogas dissemination standpoint, these problems could be attributed, in part, to the lack of thorough feasibility studies and pre-adoption evaluation of local contexts, risks and capabilities of target households before installing the biogas plants.

4.6.7. Lack of proper feasibility assessment and faulty dissemination approach

Perhaps one of the major obstacles for widespread dissemination and effectiveness of the biogas program in Ethiopia is the very approach that the technology is promoted. According to local NBPE officials interviewed, a household is expected to satisfy four key criteria to qualify for biogas adoption, and financial/technical support from the NBPE

1) Minimum cattle heads of 4-6 if local breeds or 2-3 if hybrids for a 6 m^3 plant, and 6-8 local breeds or 3-4 hybrids for 8 m^3 plant to get at least 40-60 kg of fresh dung per day
2) Access to sufficient water (at least 40 – 50 litters per day) within 1-2 km walking distance

3) Household income (as a rule a middle- or higher-income level based on local criteria)

4) Location (highland areas are less preferred due to poor anaerobic digestion in cold climates)

Whilst these criteria are commonly used by many developing countries implementing domestic biogas programs, in practice, the afore-stated criteria were rarely followed in the study districts. Apparently, many early adopters were the so-called 'model farmers' a politicized class of households based on their income and 'success' in implementing government development packages. Ironically, some of the same 'model farmers' stated that they were pressured to adopt the technology by local government administrators. Others maintained that they had their expectations inflated by biogas promoters so that they would adopt the technology. These claims suggest that the dissemination approach for at least some of the biogas plants was not demand-driven, thus contributing to the subsequent dis-adoption of the technology.

Most importantly, the current dissemination approach lacks exhaustive evaluation of crucial factors such as household labour size, the likelihood of continued cattle herding, probability of relocation to other areas, willingness and commitment of the household to ownership and regular operation of biogas, year-round availability, and reliability of water supply and prevalence of livestock diseases. Our results reinforce earlier studies [14, 16-17] that identified poor dissemination strategies and lack of thorough feasibility studies as key factors contributing to the failure of biogas plants in developing countries.

4.6.8. Costly undertaking, lack of ownership feeling and misguided perception

About half of the total installation cost of biogas plants in rural Ethiopia is covered by the government –with assistance from the European Union– in the form of subsidy; while the remaining half is covered by the household either through direct payment or through a two-year credit loan. The purpose is to offset the high up-front cost of biogas installation to the rural families and enhance the dissemination of the technology. To that end, the government provides a subsidy of ETB 7000-8000 (US$ 250-290) per biogas plant constructed regardless of the size of the digester or income of the household [21]. For the most part, the subsidy covers costs including payment for masons, purchase of digester construction materials, and purchase of biogas appliances and equipment.

Table 10. Average installation costs of a 6m^3 biogas plant in the study areas in 2018

No	Cost item	Amount in ETB	Amount in USD
1	Purchase of digester construction materials	4960	183
2	Appliances and equipment (valves, pipes, stove, lamp)	6000	221
3	Labour (mason and daily labour)	3560	131
4	Transport	482	18
5	Other miscellaneous costs	408	15
	Sub-total	15410	567
6	Interest for credit loan (15%)	2264	83
	Total	17674	650

Source (own field data, 2018) *1 USD = 27.1776 ETB in August 2018

From the analysis of the financial data collected (Table 10), the average total capital cost of a 6m^3 biogas plant in the study areas in 2018 was approx. ETB 15, 410 (US$ 567) excluding the 15 % interest rate from local credit financing institutions that should be paid back in two years period. When the 15% annual interest is included (disregarding the discounting effect), the total installation cost of a single biogas plant would be ETB 17,674 (US$ 650). This means, of the total installation cost of ETB 17, 674 (US$ 650) including interest, the government's subsidy is on average ETB 7, 544 (43%), while the contribution of the household through local credit financing loan and direct payment is ETB 10, 130 (57%). Considering the limited energy use from the biogas plants, this ETB 10,130 investment represents a huge financial burden that amounts to more than 40% of the average gross annual cash income of the rural household.

In a society where 'open access' 'free' collection of fuelwood is the principal source of domestic energy; this biogas installation cost even with such a generous government subsidy is considered costly. We found that many biogas adopters have not yet paid back their biogas loans even after many years. According to local officials, some of the biogas adopters have not paid back their loans apparently from the perception that the biogas program is the interest of non-governmental organizations and the government. And hence, they are not obliged to return the loan or to properly manage the biogas plant. Some adopters have even deliberately avoided operating the digesters assuming that the failure of the plant will evade their loan. Such misguided perceptions and lack of sense of ownership from biogas adopters have affected the time and labour they invest to keep the biogas plants working.

4.6.9. Poor quality of digester construction and installations

The faults in the biogas systems are also from the low quality of digesters' construction. Biogas owners and key informants noted that materials used in the construction of some of the digesters were of poor quality and were built by unskilled masons. As a result, the quality of the digesters and the fitting of the gas systems were poor, and it did not take long for the gas pipes to start to leak in some plants. According to local masons, however, the problem of low-quality digesters construction arises from the increase in the cost of construction materials, and labour given the budget allotted per digester.

5. Conclusions and policy implications

5.1. Concluding remarks

This study was carried out to investigate the current utilization level, energy output, and impact of household biogas systems in rural southern Ethiopia. The data were collected from a direct field study of 32 digesters, a survey of 605 rural households and track-record data of 657 biogas plants installed in four districts between 2011 and 2017. The findings showed that the uptake and utilization of biogas in rural Southern Ethiopia is generally very low. In terms of current functionality rate and energy output, the results indicated that of the total 32 biogas plants directly examined, only 21 (65.6%) were functional. Analysis of the track-record data for the 657 digesters installed in the study areas between 2011 and 2017, indicated that only 337 (51.3%) were functional in 2018. In those plants that were functional, the average quantity of biogas produced from a 6m^3 functional plant was estimated to be 0.61m^3/day. This means that the current level of biogas production could replace the consumption of 631.7 kg of fuelwood and 25 L of kerosene per household per year. However, analysis of the total energy consumption of biogas users compared with the non-users indicated that the impact of the current level of biogas production and use on the household fuelwood and kerosene consumption is insignificant, and it can only avoid 10.7% of the household's fuelwood consumption. As a result, biogas users in the SNNPRS and rural Ethiopia at large continue to depend on fuelwood and kerosene in quantities almost as much as the non-users.

Overall, the study finds that in the present situation of biogas production and usage, the potential of biogas to curb the heavy reliance of rural households on traditional woody biomass fuels and kerosene; and induce substantive energy transition towards clean cooking and lighting fuels is limited. Given the high cost of biogas installation both for the government and the rural household, the findings signify the need for a thorough revisiting of existing biogas dissemination approaches and operational practices. The root causes of the failure and inefficient use of biogas are diverse and complex. Foremost among these were the poor biogas dissemination and implementation approach, lack of maintenance services and spare parts; lack of focused biogas policy and follow-up of implementation; lack of adequate training and technical support; and poor quality of digesters' construction. From the users' side problems included; poor operation of the digesters; shortage of labour and feedstock (cow-dung); inflated initial expectations and subsequent dissatisfaction; lack of ownership feeling and misguided perceptions.

5.2. Lessons and policy implications

A successful biogas program is attainable if enabling policy environment is met by joined efforts from governments/states, the private sector, financial institutions and local and international stakeholders. To this end, the most important lessons and policy options drawn from this study and international experience are discussed hereafter.

5.2.1. Strengthening the institutional capacity of local biogas implementers

International experiences show that Ethiopia and other countries in sub-Saharan Africa can improve the effectiveness of their biogas programs by optimizing the institutional and organizational capacity of the sector through implementing a multi-stakeholder approach. This encompasses encouraging the participation of private businesses and local entrepreneurs in the biogas dissemination, installation, and marketing. To this end, governments need to create enabling policies and incentives to forge partnership and mutually beneficial cooperation among stakeholders. Provision of adequate budget and logistical support to local biogas promoters is another key intervention needed to improve the implementation capacity the biogas program.

5.2.2. Provision of timely maintenance services and availing spare parts

It is recommended that biogas maintenance centres with skilled technicians be set up at a reasonable distance to adopters. A best practice of the Nepalese and Indian biogas programs, in this line, is the imposition of mandatory after-sales services, guarantee on digesters performance after installation, guarantee on biogas appliances and annual maintenance visit for the first five years of installation [12, 40]. Concerning spare parts, governments should facilitate the import of biogas spare parts as quickly as possible. However, in the long - term the most feasible solution to the spare parts problem is the local manufacturing of spare parts.

5.2.3. Provision of financial and non-financial incentives to adopters

To increase the adoption of biogas especially by the rural poor, this study recommends the provision of long-term soft (flat-rate) loans for households who intend to adopt biogas. Along this line, the achievements of the Nepalese biogas program in securing the partnership of financial institutions in the adoption and credit financing of biogas plants is a commendable practice to learn from [40]. Improving access to credit finance and researching locally available and cheaper digester construction materials to reduce installation costs are other important points to consider.

5.2.4. Regular monitoring and follow -up, and design/quality control

To address the lack of regular monitoring and regulations, Ethiopia needs to develop and enforce basic biogas design standards and regulations. As noted by Mendis and van Nes [40], imposing strict standards for quality and design of digesters, and certification of biogas installers can ensure the quality of the digesters constructed. In addition to the quality control, building the technical capacity of biogas masons is critical.

5.2.5. Awareness creation, and building local technical capacity

An essential element of a successful biogas program is increased awareness of the rural communities on the benefits and costs of biogas through various formal and informal channels; and the training of adopters on the basics of how to operate the plant, how to use the biogas stove and lamp, and how to repair minor faults.

5.2.6. Revisiting existing biogas dissemination approaches

This paper emphasizes that biogas dissemination should be demand-driven to avoid subsequent dis-adoption and failure as experiences in Uganda have shown [17]. Most of all, biogas dissemination must be based on an exhaustive assessment of the capabilities and needs of the end-user including evaluation of long-term availability of feedstock, household's labour size, and reliability of water supply. Biogas is not a panacea for all the problems of rural households. It has its trade-offs, and adopters need to be made fully aware of the high costs, and significant labour and time investments it requires.

6. References

1. Gaye, A. (2008). Access to energy and human development. United Nations Development Programme (UNDP). Human development reports, 2008. http://hdr.undp.org/en/content/access-energy-and-human-development (Accessed 15. 02. 19).
2. IEA. (2017). Share of total primary energy supply of Ethiopia in 2016. International Energy Agency, 2017. http://www.iea.org/stats/WebGraphs/ETHIOPIA4.pdf *(*Accessed 10.05.19*).*
3. MoME. (2010). Energy Policy of Ethiopia. Ministry of Mines and Energy of the Federal Democratic Republic of Ethiopia, Addis Ababa. https://eneken.ieej.or.jp/data/3195.pdf ((Accessed 18. 02. 19).
4. Guta, D.D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. Energy Policy, 75: 217-227.
6. World Bank. (2018). Rural population (% of total population) Ethiopia 2018. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS?locations=ET (Accessed 01. 01.19)
7. WHO. (2009). World Health Organization. The energy access situation in developing countries. A Review Focusing on the LDC and Sub-Saharan Africa. https://www.undp.org/content/dam/undp/library/Environment%20and%20Energy/Sustainable%20Energy/energy-access-situation-in-developing-countries.pdf (Accessed 10. 05. 19)
8. Boers, W., Workneh, K., Eshete, G. (2008). National Biogas Program of Ethiopia, Program Implementation Document. Ethiopia Rural Energy Development and Promotion Centre, SNV/Ethiopia. http://www.snvworld.org/download/publications/nbp_implementation_document_ethiopia_2008.pdf. (Accessed 14.05.19)
9. Kamp, L.M., Forn, E.B. (2016). Ethiopia's emerging domestic biogas sector: Current status, bottlenecks and drivers. Ren. Sustain. Energy Rev, 60: 475-88.
10. Bedi, A.S., Sparrow, R., Tasciotti, L. (2017). The impact of a household biogas program on energy use and expenditure in East Java. Energy Economics, 68: 66-76
11. Laramee, J., Davis, J. (2013). Economic and environmental impacts of domestic bio-digesters: Evidence from Arusha, Tanzania. Energy for Sustainable Development, 17(3): 296–304.
12. Katuwal, H., Bohara, A.K. (2009). Biogas: A promising renewable technology and its impact on rural households in Nepal. Renewable and Sustainable Energy Reviews 2009; 13(9): 2668-2674.
13. Bhat, P.R., Chanakya, H.N., Ravindranath, N.H. (2001). Biogas plant dissemination: success story of Sirsi, India. Energy for Sustainable Development, 5(1):39-46.

14. Ghimire, P.C. (2013). SNV-supported domestic biogas programmes in Asia and Africa. Renew. Energy, 49: 90-94.
15. Mulinda, C, Hu, Q., Pan, K. (2013). Dissemination and Problems of African Biogas Technology. Energy and Power Engineering, 5: 506-512.
16. Mengistu, M.G, Simane, B., Eshete, G., Workneh, T.S. (2015). A review on biogas technology and its contributions to rural livelihood in Ethiopia. Ren Sust. Energy Rev., 48:306–316.
17. Parawira, W. (2009). Biogas technology in sub-Saharan Africa: status, prospects and constraints. Reviews in Environmental Science and Bio/Technology, 8(2):187–200.
18. Lwiza, F., ..., Balana, B.B. (2017). Dis-adoption of Household Biogas technologies in Central Uganda. Energy for Sustainable Development, 37: 124-132.
19. Erick, M. K., Kirubi, G., Muriuki, S. (2018). Key Factors Influencing Adoption of Biogas Technology in Meru County, Kenya. J Envi. Science, Toxicology and Food Tech, 12(3): 57-67.
20. Osei-Marfo, M., Awuah, E., de Vries, N.K. (2018). Biogas technology diffusion and shortfalls in the central and greater Accra regions of Ghana. Water Practice and Technology,13(4): 932-946.
20. Berhe, M., Hoag, D., Tesfay, G., Keske, C. (2017). Factors influencing the adoption of biogas digester in rural Ethiopia. Energy, Sustainability and Society, 7(10).
21. Mengistu, M.G, Simane, B., Eshete, G., Workneh, T.S. (2017). Institutional Factors Influencing the Dissemination of Biogas Technology in Ethiopia. J. of Human Ecology, 55(1,2):117-134.
22. Zhang, L.X., Wang, C.B., Song, B. (2013). Carbon emission reduction potential of a typical household biogas system in rural China. J of Cleaner Production, 47:415-421.
23. Bond, T., Templeton, M.R. (2011). History and future of domestic biogas plants in the developing world. Energy Sustain. Dev., 15: 347–354.
24. Chang, I. S., ..., Yang, Y. (2014). A time-geographical approach to biogas potential analysis of China. Renew Sustain Energy Rev, 37: 318 -333.
25. Surendra, K., Takara, D., Hashimoto, A.G., Khanal, S.K. (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. Renew. Sustain. Energy Rev., 31, 846–859.
26. CSA. (2013). Federal Democratic Republic of Ethiopia, Population Projection of Ethiopia for All Regions from 2014 – 2017. Central Statistical Agency, Addis. https://www.scribd.com/document/343869975/Population-Projection-At-Wereda-Level-from-2014-2017-pdf (Accessed 17. 01. 18)
27. Cochran, W.G. (1977). Sampling Techniques, 3rd ed. Wiley New York, USA.
28. Khandelwal, K.C., Gupta, V.K. (2009). Popular Summary of the Test Reports on Biogas Stoves and Lamps from Testing Institutes in China, India and the SNV. http://www.bibalex.org/Search4Dev/files/338195/171754.pdf (Accessed 22. 04. 19).

29. Chambers, R. (1988). Direct matrix ranking (DMR) in Kenya and West Bengal. RRA Notes No 1. International Institute for Environment and Development. IIED, London.
30. IRENA. (2016). Measuring small-scale biogas capacity and production. International Renewable Energy Agency (IRENA), Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Statistics_Measuring_small-scale_biogas_2016.pdf (Accessed 20.05.19)
31. SNV. (2019). The Africa biogas partnership program (ABPP), SNV Ethiopia. https://www.africabiogas.org/countries/ethiopia/ (Accessed 10.03.19)
32. Eshete, G., Sonder, K., Heegde, F. (2006). Report on the feasibility study of a national programme for domestic biogas in Ethiopia. Netherlands development organization (SNV). http://www.bibalex.org/Search4Dev/files/338849/172350.pdf (Accessed 03. 01. 19)
33. Schwarz, D. (2007). Biogas Technology. GIZ, Germany . https://energypedia.info/images/2/2e/Biogas_Technology.pdf (Accessed 01.01.19)
34. Yimer, S., Yimer, B., Sahu, O. (2014). Biogas Production Using Geomembrane Plastic Digesters as Alternative Rural Energy Source and Soil Fertility Management. Sustainable Energy, 2 (1): 12-19.
35. Subedi, S.K.A. (2015). Domestic biogas production and use in Nepal: a simple, reliable, clean and cost-effective solution to provide energy security to the rural households. A PhD thesis, Massey University, New Zealand.
36. Somanathan, E., Bluffstone, R. (2015). Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change. World Bank's Development Research Group; Environment and Energy Team. Policy Research Working Paper No 7349.
37. Bedi, A.S., Pellegrini, L., Tasciotti, L. (2015). The Effects of Rwanda's Biogas Program on Energy Expenditure and Fuel Use. World Development, 67: 461 – 474.
38. DFID. (2012). The Potential of Small-Scale Biogas Digesters to Improve Livelihoods and long-Term Sustainability of Ecosystem Services in Sub-Saharan Africa. Quarterly Report, UK. http://www.64d.dfid.gov.uk (Accessed 12.04. 19)
39. Bajgain, S., Shakya, I., Mendis, M.S. (ed.). (2005). The Nepal biogas support program: a successful model of public private partnership for rural household energy supply. Full report, SNV. http://siteresources.worldbank.org/INTENERGY/Publications/20918309/NepalBiogasSupportProgram.pdf (Accessed 18. 05. 19)
40. Mendis, M.S., van Nes. W.J. (1999). The Nepal Biogas Support Program: Elements for Success in Rural Household Energy Supply. Policy and best practice, SNV,. http://www.bibalex.org/Search4Dev/files/284918/117213.pdf (Accessed 12. 04. 19)

Appendix I: Current operational status of biogas plants installed between 2011-2017

		6m^3		8m^3					
	Year installed	Operat.	Non-operat.	Operat.	Non-operat.	Total operat.	Total non-operat.	Total installed	% Operati.
Aleta-wondo	2011	16	29	0	2	16	31	47	34.0
	2012	38	66	0	0	38	66	104	36.5
	2013	31	37	1	1	32	38	70	45.7
	2014	8	6	0	0	8	6	14	57.1
	2015	9	8	0	0	9	8	17	52.9
	2016	30	12	0	0	30	12	42	71.4
	2017	10	2	2	0	12	2	14	85.7
		142	160	3	3	145	163	308	47.1
Boloso-sore	2011	0	0	0	0	0	0	0	0.0
	2012	8	5	4	2	12	7	19	63.2
	2013	12	4	0	0	12	4	16	75.0
	2014	7	4	0	0	7	4	11	63.6
	2015	10	2	0	0	10	2	12	83.3
	2016	17	12	0	0	17	12	29	58.6
	2017	9	10	0	0	9	10	19	47.4
		63	37	4	2	67	39	106	63.2
Cheha	2011	4	3	0	3	4	6	10	40.0
	2012	8	9	2	8	10	17	27	37.0
	2013	10	11	4	9	14	20	34	41.2
	2014	3	7	3	8	6	15	21	28.6
	2015	1	0	5	3	6	3	9	66.7
	2016	2	3	1	0	3	3	6	50.0
	2017	1	0	0	0	1	0	1	100.0
		29	33	15	31	44	64	108	40.7
Mirab-abaya	2011	16	13	2	1	18	14	32	56.3
	2012	18	26	2	1	20	27	47	42.6
	2013	11	4	1	1	12	5	17	70.6
	2014	4	2	3	0	7	2	9	77.8
	2015	11	2	0	0	11	2	13	84.6
	2016	10	2	0	0	10	2	12	83.3
	2017	3	2	0	0	3	2	5	60.0
		73	51	8	3	81	54	135	60.0
	Total	307	281	30	39	337	320	657	51.29

Paper III

Analysis of potential fuel savings, economic and environmental effects of improved biomass cookstoves in rural Ethiopia

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Abstract

Unsustainable utilization of biomass fuels with inefficient traditional cooking stoves has been a major challenge to ensuring energy and environmental security in rural Ethiopia. This study analyses the potential fuel savings, economic and environmental effects of three improved biomass cookstoves (ICSs): *Mirt*, *Gonziye,* and *Tikikil* in rural southern Ethiopia based on data collected from a cross-sectional survey of 605 households and direct energy consumption measurements in four districts. Inferential statistics and cost-benefit analysis were used to analyse the data. The results showed that compared with the traditional three-stone open fire tripod; usage of ICSs could reduce household fuelwood consumptions on average by 1.72 to 2.08 tons per household per year. These fuelwood savings translate to potential emissions abatement of 2.82 to 3.43 tCO_2e per stove per year. The results from the cost-benefit analysis indicated that investment in these ICSs could provide a net economic benefit of between US$ 317 and US$ 460 during the 2 to 5 years lifespan of the stoves. The benefit-cost ratios of the ICSs were calculated between 19.6:1 and 42.0:1. The findings suggest that promoting the use of *Mirt*, *Gonziye* and *Tikikil* stoves is a viable option and key component of the strategy for improving the energy-efficiency and well-being of rural communities while contributing to sustainable biomass utilization, and mitigation of climate change in Ethiopia and beyond.

Keywords: *Rural households, improved biomass cook-stoves, fuel-savings,* CO_2 *emissions reduction, cost-benefit analysis, sustainable biomass utilization*

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List of Notations and Abbreviations

Notation/Abbreviation	Description
B_{bh}	Benefit due to Better Health
B_{bsf}	Benefit Due to Better Soil Fertility
BC	Black Carbon
BCR	Benefit -Cost Ratio
B_{cts}	Benefit due to Fuel Collection and Cooking Time Savings
B_{er}	Benefit due to Emission Reductions
B_{fs}	Benefit due to Fuel Savings
B_{pfc}	Benefit due to Preserved Forest Cover
CBA	Cost-Benefit Analysis
CCT	Controlled Cooking Tests
CO_2e	Carbon dioxide Equivalent
EESRC	Ethiopian Energy Study and Research Centre
EREDPC	Ethiopian Rural Energy Development and Promotion Centre
EUA	European Union's Carbon Emission Allowance
GIZ	German Development Agency
ICSs	Improved Cookstoves
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
Kebele	A cluster of villages (neighbourhoods), the smallest administrative unit of Ethiopia
NPV	Net Present Value
P	Price
SNNPRS	Southern Nations Nationalities and Peoples Regional State
TEB	Total Economic Benefit
W	Wage
WBT	Water Boiling Tests
Woreda	District (cluster of kebeles), the third-level administrative divisions of Ethiopia after Regional state and Zone

1. Introduction

The energy regime of most developing countries is dominated by traditional solid fuels (Foell et al., 2011). Recent estimates show that over 890 million people in sub-Saharan Africa depend on traditional fuels (mainly fuelwood, crop residues, charcoal, and dung-cakes) as their primary energy sources for cooking (IEA, 2018a). This overreliance and unsustainable use of biomass fuels, in particular fuelwood and charcoal, with inefficient traditional cookstoves, has been among the major drivers of depletion of natural forests in the region (Mwampamba, 2007; Ndegwa et al., 2016; Obiri et al., 2014; Putti et al. 2015). The incomplete combustion of biomass fuels in traditional stoves has an adverse effect on human health and the climate due to the formation of black carbon, a potent global-warming agent (Wathore et al., 2017). Cooking with traditional cookstoves also induces substantial negative socio-economic impacts by reducing the time households spend on education and productive economic activities (Jeuland and Pattanayak, 2012).

In the context of Ethiopia, where the household sector is the major consumer of energy, biomass accounted for 91.4% of the total primary energy consumed in the country in 2016 (IEA, 2018b; Mondal et al., 2018). In rural areas where approx. 80% of Ethiopia's population lives, almost all of the household energy demand for cooking is met by solid biomass fuels (Gebreegziabher, 2007). As rightly noted by Haile et. al (2009, p. 30], "In Ethiopia, household energy means rural energy and rural energy means biomass". This heavy dependence on woody biomass fuels and the inefficient energy utilization from a traditional open-fire stove with low thermal efficiency (13-15%) has exacerbated the degradation of Ethiopia's remaining forests (Beyene and Koch, 2013; Guta, 2014). According to the Ethiopian Forestry Action Program (EFAP, 1994), Ethiopia's projected demand for fuelwood for 2014 (88.9 million m^3) was ten times as much as the annual sustainable supply (8.8 million m^3). This has direct implications on the sustainability of biomass utilization, biodiversity conservation, and climate-resilience of the country.

Against the backdrop of the growing energy-environment predicament, the government of Ethiopian with the technical assistance from the German Development Agency (GIZ) and other partners has been promoting and disseminating various models of improved cookstoves (ICS) since 1998 (Megen Power, 2008). The goal is to improve household energy efficiency and mitigate the adverse environmental, economic, and health impacts of unsustainable and inefficient use of biomass fuels (Beyene and Koch, 2013). In view of this, the Ministry of Environment, Forest and Climate Change of Ethiopia (MEFCC, 2017) has reported that by 2017, an estimated 15 million ICSs had been disseminated in the country through various stove projects and private commercial stove producers. The main types of ICSs disseminated include; *Mirt* [1]*Injera* baking stove; *Gonziye* cooking and injera baking stove; *Institutional Rocket* cooking stove; *Tikikil* cooking stove, and *Lakech* and *Merchaye* charcoal-burning cooking stoves.

Several studies indicate that the use of ICSs provides multiple and significant benefits to households and the global community (Brooks et al., 2016; García-Frapolli et al., 2010; Pine et al., 2011). These benefits extend from reducing biomass fuel consumption and improving the health and economic conditions of households to increased conservation of forests and reduced emissions of Greenhouse gases (GHGs) (Bailis, et al., 2007; Bensch and Peters, 2015). For instance, a study by Bailis et al. (2007) in India and Mexico, by using laboratory-based [2]Water Boiling Tests (WBTs) and [3]Kitchen Performance Tests (KPTs), found that application of ICSs could reduce the average daily per capita fuel use of households by 19 to 67% compared to traditional stoves. A [4]Controlled Cooking Test (CCT) conducted by Gebreegziabher et al., (2018) in Ethiopia found that compared with a traditional three-stone tripod, the use of '*Mirt'* improved stove provides fuel savings of 22% to 31%. By using CCTs and survey evaluation, Adkins et al. (2010) in rural Uganda and Tanzania also showed that, compared to the traditional stove, ICSs were 22 to 46% more efficient in terms of fuelwood use per household per year. A CCT experiment by Beyene et al. (2015) in rural Ethiopia also found that on average one ICSs (*Mirt* stove) saves 634 kg of fuelwood per year, which translates to an emissions reduction of 0.94 tons CO_2e per user household per year.

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[1] *'Injera'*- is a thin round flatbread consumed as a staple food in much of Ethiopia

[2] Water Boiling Test (WBT) is a simplified simulation of a cooking process through replicable standard tests to measure how efficiently a stove uses fuel to heat (boil) water in a cooking pot (GIZ-HERA, 2018)

[3] Kitchen Performance Test (KPT) is a field–based procedure to assess the performance of improved stove(s) on fuel consumption in the kitchens of real households (GIZ-HERA, 2018)

[4] A Controlled Cooking Test (CCT) is a test conducted to compare the performance of improved stoves relative to a traditional stove by performing standard cooking tasks under a controlled environemnt.

A comprehensive systematic review by MacCarty et al. (2010) and Thomas et al. (2015) on the effects of ICSs in reducing household air pollution and CO_2 emissions concluded that use of ICSs can significantly reduce households' exposure to dangerous indoor-air pollution resulting from the biomass fuel smoke and abate emissions of CO_2e by up to 75%, compared to traditional stoves.

Whilst the literature discussed above offer valuable insight, a closer examination of the studies on ICSs in Ethiopia reveals that much of the research has been on the adoption of ICS (e.g. Eshetu, 2014; Legesse et al., 2015). The few studies carried out to assess the effect of ICSs were mostly based on CCTs and WBTs (Beyene et al., 2015; Gebreegziabher et al., 2018). As such, little is known about the actual impact and welfare implication of ICSs when applied in the normal rural setting subject to various limiting factors. This is because, though CCTs and WBTs simulate the actual cooking tasks, the methods may not accurately predict the outcomes of uncontrolled use of ICSs in the daily cooking routines of rural households involving simultaneous use of different stoves and fuels (Bensch and Peters, 2015). Moreover, outside of the controlled environment, many factors stemming from the characteristics, energy access and availability, location, and cooking habits of the households can affect the efficiency, usage, and overall impact of the ICSs.

The aim of this study was thus to empirically analyse the fuel-savings and economic and environmental effects of three improved biomass cookstoves in rural southern Ethiopia based on data from a cross-sectional survey of sample households in conjunction with direct fuel consumption measurements and cooking observations. By doing so, the study seeks to provide a more practical assessment of the economic and environmental effects and contributions of ICS use on household energy efficiency and sustainable utilization of biomass resources in rural Ethiopia and sub-Saharan Africa at large.

2. Description of ICSs investigated

According to the Global Alliance for Clean Cookstoves (2012), the market penetration (in terms of percentage of user households) of the most widely used ICSs in Ethiopia in 2012 were estimated at 13% for *Mirt*, 2% for *Gonziye,* 0.50% for *Tikikil*, and 0.50% for *Lakech* stoves. This study focuses on the first three ICSs (*Mirt*, *Gonziye,* and *Tikikil*), all of which are wood-burning, and their brief description is presented hereafter.

2.1. Mirt Injera baking wood-burning stove

'*Mirt'* is a fuelwood-burning stove specialized for baking *'Injera'*- Ethiopian bread. It was developed in 1991 by the Ethiopian Energy Study and Research Centre (EESRC) which later became the Ethiopian Rural Energy Development and Promotion Centre (EREDPC) (Megen Power, 2008). It is made of cement and sand/scoria and has six components. The first four cylindrical components of 4-6 cm thickness make up an enclosure, that has two openings (Figure 1). The other two components are fitted with the enclosure by overlaying one on top of the other to regulate the flow of smoke in the stove and provide a rest for the cooking pot (GIZ-ECO, 2011).

Figure 1. a) *Mirt* stove without *Injera* baking plate; b) *Mirt* stove with injera baking plate

The main fuel used in *Mirt* stove is fuelwood and to a lesser extent other solid biomass fuels such as crop residues. CCTs results show that *Mirt* stove has a fuel-saving efficiency of up to 50% (GIZ-ECO, 2011). The price of one *Mirt* stove in the study areas in 2018 was between Ethiopian Birr (ETB) 150 and 250 (≈ US$ 5.5- US$ 9.2).

2.2. Gonziye multi-purpose wood-burning stove

Gonziye is a multipurpose stove developed as an affordable and fuelwood-efficient stove suitable to rural areas by the Ethiopian Ministry of Water, Irrigation and Electricity (GIZ-ECO, 2014). It is made of burned clay with a mould (see Figure 2). *Gonziye* is designed in such a way that it can be adjusted to suit both for *Injera*-baking (Figure 2a) and cooking (Figure 2b) purposes. Wood is the main fuel used in *Gonziye.* Results from CCTs show that compared to the traditional open-fire stove, *Gonziye* has a fuel efficiency of 42% for cooking and 54% for baking (GIZ-ECO, 2014). It is the cheapest ICS with prices between ETB 70 and 80 (≈ US$ 2.5 - $2.9) in 2018.

Figure 2. a) *Gonziye* stove set up for baking injera; b) Cooking with *Gonziye*

2.3. Tikikil wood-burning cooking stove

Tikikil is a wood-burning rocket cooking stove (see Figure 3b) designed to accommodate 25 -33 cm diameter pot depending on the model (single-skirt with a fixed 25 -27 cm diameter skirt and double-skirt with two rings of 27 cm and 33 cm diameter skirts) (GIZ-ECO, 2010). It is made of a cylindrical inner clay liner as a combustion chamber, covered with galvanized sheet metal on the outside. Wood is the main fuel used in *Tikikil*. CCTs results have shown that *Tikikil* has a fuel-saving potential of up to 50% compared to the traditional three-stone tripod (Figure 3a). The price of one *Tikikil* stove in 2018 in the study areas ranged between ETB 180 and 200 (≈ US$6.6 - $7.4).

Figure 3. a) Traditional open-fire tripod b) *Tikikil cooking* stove

3. Materials and Methods

3.1. Study areas and sampling

The study was conducted in four rural districts of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia. The four districts were Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya (see Figure 4). The SNNPRS lies between Latitudes 4°43'- 8°58' North and Longitudes 34°88' - 39°14' East. Administratively, the region is divided into 14 zones and 4 special *woredas* (districts) consisting of a total of 137 rural districts and 22 urban administrations (CSA, 2013). The *woredas* (districts) are further subdivided into *kebeles* (neighbourhoods), the smallest administrative units of Ethiopia. The total population of the region was estimated at 19. 2 million in 2017, of which 90% were rural inhabitants made up of 2,743,502 households in 3,709 *kebeles* and 10% were urban inhabitants composed of 367,493 households in 324 *kebeles* (CSA, 2013).

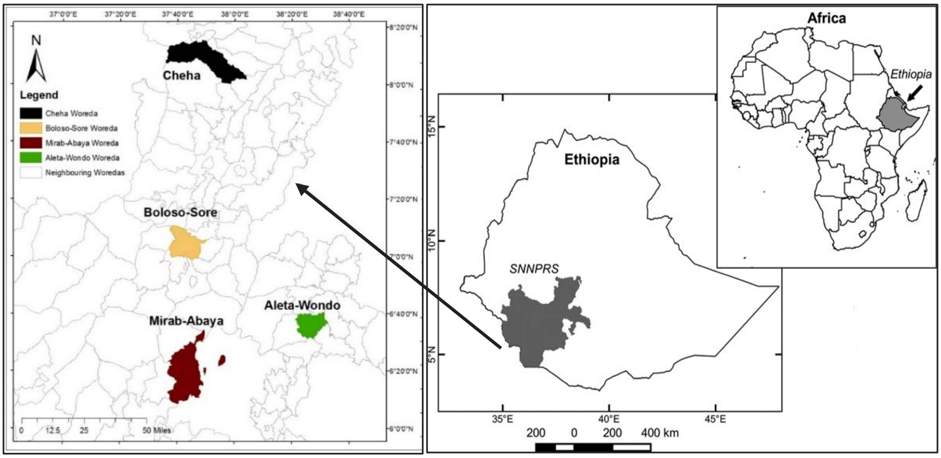

Fig 4. Location map of the SNNPRS and study districts (*woredas*)

A multi-stage stratified random sampling approach was used to select sample districts and households for the study. In the first stage, 23 rural districts (out of the 137 rural districts) where ICSs intervention has been active over the past decade were identified based on data from the Regional Mines and Energy Agency, and the Central Statistical Agency (CSA, 2013). This was needed for the study to represent the rural population with access to ICSs. The 23 districts were then clustered into three groups as highland, midland, and lowland categories based on their agro-ecological conditions.

The purpose of clustering the districts was to contain potential effects of agro-ecology dependent local factors and fuel sources on adoption and usage of ICSs. Subsequently, two districts from the highland, one from the midland and one from the lowland were randomly chosen. Two districts were selected from the highland category because more than half of the 23 districts identified fell into this category. Hence, Aleta-wondo and Cheha were selected from the highland category; while Boloso-sore and Mirab-abaya districts were selected from the midland and lowland respectively.

The total estimated population of Aleta-wondo district in 2017 was 187,957 comprised of 33, 738 households; and that of Cheha was 122,770 composed of 24,554 households (CSA, 2013). The total population of Boloso-sore district in 2017 was estimated to be 187,558 made up of 36,410 households and that of Mirab-abaya was 90, 508 composed of 12,784 households. Accordingly, in the second stage, a representative sample size for the study was determined at 95% confidence level, 4% precision (for smaller allowable error between the sample estimates and the true population values) and p = 0.5 (for most conservative estimates/ large sample size) following Cochran (1977) as:

$$N = \frac{(z^2 \boldsymbol{\alpha}/_2)\ (p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\ .\ (0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:

N= is the desired sample size

P = 0.5 is the assumed population proportion expected to have access to renewables

e= 0.04 is the desired precision (or margin of error) at 4%

$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size was determined at 660. This total sample size was then distributed to the selected four study districts by using the probability proportional to the household size (PHS) method. Thus, of the total 660 sample size, 207 were allotted to Aleta-wondo district, 224 to Boloso-sore, 151 to Cheha district, and 78 to Mirab-abaya. In the third stage, three *Kebeles* were randomly chosen in each district and the sample size allotted for each district was distributed to the three kebeles by using the same PHS method.

Finally, a random selection of sample households was made from a complete list of all households in each *Kebele* using a lottery method. The main reason for the random selection of sample households, as opposed to purposive sampling, was to ensure that the data collected are representative of the true population structures.

3.2. Data sources and collection methods

3.2.1. Household Survey

Primary data were gathered from a cross-sectional survey of the 660 sample households by using semi-structured questionnaires that were administered through face-to-face interviews by the researchers and trained data collectors. The survey questionnaires were designed based on the objectives of the research and review of relevant literature. To ascertain that the data collected are accurate, reliable, and representative; several considerations were made during the designing of the data collection instruments. The major consideration included identifying the characteristics of the target population and ensuring that questions are designed to address the research problem and represent the diverse demographic and socio-economic classes in the population. Other points taken into consideration include the use of local measurement units, application of multiple (cross-validating) measures, and balancing of open and close-ended questions.

For that purpose, preliminary studies were carried out in each study district prior to the questionnaires designing, and relevant information was gathered. This was followed by a systematic development of the questionnaire and pretesting on 24 randomly selected households (both ICS users and non-users) in the study areas. The results from the pre-test were used to improve and fine-tune the survey instruments. The actual survey was finally conducted between January and December of 2018 in such a way that sample households in each district were randomly assigned to the four seasons in Ethiopia to contain potential effects of seasonality on fuel availability and ICS use. Data gathered from the surveys included: demographic, location, and socio-economic characteristics; ownership and type of ICS; utilization frequency; supply source and cost of ICSs; cooking and *Injera* baking fuel choices, and consumption quantities; family members involved in and time spent for fuelwood collection and cooking/baking.

3.2.2. Direct ICS use/adoption and fuel consumptions measurement

To verify household adoption and utilization of ICSs, direct observation, and validation was conducted for each household that reported owning ICSs. To accurately estimate the fuel consumption of households and minimize potential data inaccuracy from the self-reported survey data, a direct measurement of fuel consumption and observation of kitchen cooking practices of 48 households (24 ICS users and 24 non-users) from within the 660 total samples was conducted. Selection of the 48 households was made such that 6 ICS users and 6 non-users were randomly chosen from each study district. To quantify household consumptions of solid biomass fuels, first, the most common local biomass fuel delivery modes and units were identified for each fuel type. Afterwards, random samples were taken for each fuel type and delivery mode from local markets, biomass fuel collectors, retailers, and consumers. The weight of each fuel delivery mode was then measured by using a weight scale and average values were calculated for each delivery mode and fuel type as summarized in Table 1.

Table 1. Measurement of common biomass fuels delivery modes in the study areas

Fuel types	Delivery modes	Local units	Number of samples	Average weight (kg)
Fuelwood	Donkey-cart load	Load	10	116.70
	Donkey-backload	Load	12	48.02
	Human backload	Bundle	14	30.03
	Human headload	Bundle	12	24.50
Agri-residues	Human backload	Bundle	7	20.67
	Sack	Large	8	41.90
	Basket (bale)	Medium	6	18.45
Charcoal	Sack	Small	7	23.48
	Sack	Large	8	50.12
Dung cakes	Sack	Small	8	20.02
	Sack	Large	5	41.17
	Basket	Medium	6	19.56

By using the average weights calculated and the local fuel delivery modes, the daily and weekly fuelwood, charcoal, agri residues and dung-cakes consumption of the 48 case-study households were directly measured by the researchers and data enumerators for two consecutive weeks. The data collected from the direct measurements were used to triangulate the survey data and establish benchmarks for ICS-users and non-users. This was followed by the quantification of the weekly and monthly fuel consumption of the total sample households by using the average weights estimated earlier and the survey data. Besides, data on various research variables were gathered from the actual kitchen cooking observational studies conducted with the 48 case-study households.

3.2.3. Key informant interviews and secondary data:

Key informant interviews were conducted with a total of 24 informants involving ICSs user female household-heads, local and district levels ICSs promoters; NGOs, and private ICS producers' associations and retailers. The key informants were selected based on their knowledge and role in ICSs production, promotion, and usage in the study districts and the SNNPRS. In addition, secondary data were gathered from various reports of the Ethiopian government, GIZ, and published and unpublished research works.

3.3. Data analysis

3.3.1. Descriptive and inferential statistics

Descriptive statistics and cross-tabulations were used to compute ICS adoption rates by district and summarize characteristics of sample households. An independent samples Welch's t-tests, Pearson's Chi-square (χ^2) test, and biserial correlation coefficients were computed to determine the significance of differences in mean values of explanatory variables between ICSs users and non-users, and measure the direction and strength of the relationship between ICS use and household fuelwood consumption.

3.3.2. Quantitative estimations and analysis

As described in section 3.2., the estimation of average household fuel consumption was made by using the data collected through direct energy consumption measurements and household surveys. The estimations were first made on a daily and weekly basis and extrapolated to a monthly and annual basis. The results were then used to calculate total household energy consumptions, average woodfuel savings, CO_2e emission reductions and time savings of ICS users (intervention groups) against non-users (control groups) wherein the latter are solely dependent on traditional open-fire tripod.

3.3.3. Economic evaluation and environmental effects analysis

A cost-benefit analysis (CBA) was carried out to analyse the net benefits of each ICS to the rural community. The CBA was conducted following methods used by Habermehl (1999; 2007) in Uganda and Malawi. The reason for adopting Habermehl's approach was that many aspects and variables of the ICSs interventions in the study areas were similar to those studied by Habermehl in Uganda and Malawi, besides being initiated and supported by the same organization, GIZ.

Using Habermehl's approach, the Total Economic Benefits of an ICS can be expressed as:

$$\mathrm{TEB} = (\mathrm{B_{fs}} + \mathrm{B_{cts}} + \mathrm{B_{er}}) + (\mathrm{B_{bh}} + \mathrm{B_{pfc}} + \mathrm{B_{bsf}}) \qquad (2)$$

Where TEB is the total economic benefit, B_{fs} is the benefit due to fuel-savings, B_{cts} is the benefit due to fuel collection and cooking time savings, B_{er} is the benefit due to emission reductions, B_{bh} is the benefit due to better health, B_{pfc} is the benefit due to preserved forest cover and B_{bsf} is the benefit due to better soil fertility.

From the findings of Habermehl (2007), parameters in the first parenthesis in Equation (2) accounted for 84.23% of the total economic benefits of ICSs disseminated in Uganda. Thus, in this study, the economic benefits of ICSs is mainly assessed by estimating these parameters $(B_{fs} + B_{cts} + B_{er})$ whereas the values for parameters in the second parenthesis (Equation 2) is deduced (estimated) based on the findings from the first parameters due to unavailability of data to quantify them. The main evaluation criteria used to measure the economic efficiency of the ICSs are Net Present Values (NPV), Benefit - Cost Ratios (BCR) and Internal Rate of Return (IRR).

Following Pearce et al. (2006), the NPV of each ICS can be mathematically expressed as:

$$\mathrm{NPV} = \Sigma((\mathrm{B_t} - \mathrm{C_t})/(1 + \mathrm{i})^{\mathrm{t}}) > 0 \qquad (3)$$

Where: B_t is the total gross benefits, C_t the total cost, t is the time horizon (the economic lifespan of the stove), and '*i*' is the discount rate (real).

The Benefit-Cost Ratio (BCR) of each ICS can be mathematically expressed as

$$\text{BCR} = \Sigma(\text{PV benefits})/\Sigma(\text{PV costs}) \qquad (4)$$

Where: PV benefits and PV costs are the present values of benefits and costs respectively

The Internal Rate of Return (IRR) of investment for each ICS can be expressed as:

$$0 = NPV = \sum_{t=0}^{n} (\text{CF}_t)/(1 + IRR)^t \qquad (5)$$

Where: NPV is the net present value of the stove, CF_t is the net cash flow in each year, IRR is the internal rate of return, t is each period and n is the lifespan of the stove.

Estimation of the CO_2e emission reduction from the use of each ICSs was made by using the Intergovernmental Panel on Climate Change (IPCC, 2006) fuelwood from dry weight to CO_2e conversion factor. Local market prices were used to estimate economic benefits from avoided fuelwood purchases (fuelwood cost savings). Shadow prices and shadow wages were calculated and used to monetarily value benefits from fuelwood collection reductions, and fuelwood collection and cooking time savings.

The shadow wage of an hour spent by a household member on fuelwood collection (W) was estimated by assuming 80% worth of the local hourly wage rate for unskilled casual daily labour following the work of Atampugre (2014), From this, the shadow price (p) of a kg of fuelwood collected from local forests and own homegardens was estimated as:

$$p = \left(\frac{\text{Average total hours spent for fuelwood collection per year by ICSs user}}{\text{Average total fuelwood collected per year by ICSs user}}\right) * W \qquad (6)$$

The European Union’s Carbon emission allowance (EUA, 2018) average auction price in August 2018 (€18.75/tCO_2e) was used to monetarily value the benefits of each ICSs from avoided CO_2e emissions.

4. Results and Discussions

4.1. Characteristics of sample households

Of the total 660 sample households determined for the study, 605 completed the survey. Whereas the data collected from the remainder 55 were either incomplete or hugely inaccurate when cross-validated and therefore excluded. The overall response rate was thus 91.70%. As shown in Table 2, of the 605 households that completed the survey, 189 (31%) were from Aleta-wondo district, 204 (34%) from Boloso-sore, 134 (22%) from Cheha and 78 (13%) were from Mirab-abaya. With respect to ICS adoption, of the total 605 sampled households, 133 (22%) own at least one type of ICS ([5]ICS-users) while the remainder 472 (78%) were non-users and almost exclusively depend on the traditional open-fire tripod (see section 4.2. for further discussions).

Table 2. Demographic and socio-economic characteristics of sample households

Variables		Stat.	Total samples (N = 605)	SE
Location/district	Aleta-wondo		189	
	Boloso-sore		204	
	Cheha		134	
	Mirab-abaya		78	
Gender of HH head	Male	Freq.	509	
	Female	Freq.	96	
Age of HH Head		Mean	48.30	10.92
Education		Mean	4.73	3.77
HH size		Mean	6.24	2.38
Total landholding in hectare (ha)		Mean	0.70	0.64
Cattle heads		Mean	3.50	2.36
Gross annual cash income in Eth. Birr		Mean	22, 155	22,350
Access to credit service		%	35.04	
Grid connected HHs		%	32.06	
Round-trip walking distance to forest (wood source), minutes		Mean	62.40	75.20
Round-trip walking distance to market, minutes		Mean	105.20	35.20

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[5] In this study *ICS users* refers to households who are actively utilizing improved biomass cook stoves for cooking and/or baking purposes besides the traditional open-fire tripod; whereas *ICS non-users* refers to those households who are exclusively dependent on traditional stoves for cooking and baking purposes.

In terms of gender, 84.13% (509) of the households surveyed were male-headed while 15.87% (96) were female-headed. The average age of respondents was 48.30 years and the average education level of the household -heads, measured in terms of the number of years of schooling completed, was 4.73. The average household size was estimated at 6.24 and the average cattle heads size per household was found to be 3.50. On the other hand, the total landholding size per household was on average 0.7 ha, and the average gross cash income per household was about ETB 22,155 (US$ 815) per year.

The fraction of sample households who have access to credit finance was 35%, and the fraction of sample households that are connected to the national grid (Ethiopia's main electricity supplier) was 32%. The average walking distance between the household's home and the nearest wood source (state/communal forests and farmland) was 62.4 minutes (round-trip), and the average walking distance between the household's home and the local market was 105.2 minutes (round-trip).

4.2. Distribution of ICSs studied

From the direct assessment of ICSs adoption, it was found that a total of 133 households (22%) were using ICSs during the study period (Table 3). This may suggest that approx. one in five households in the study areas currently uses ICSs for cooking and/or baking end-uses. However, this 22% ICSs adoption rate should be taken as a rough estimate (indicator) specific to the study areas and hence may not necessarily reflect the actual adoption rate and diffusion of ICSs in the entire region.

Table 3. Distribution of improved biomass cook stoves in the study areas

Districts	Traditional stoves		Improved Biomass Cookstoves				Total ICSs users	(%) ICS users
	Trad. open fire stove	Trad. charcoal stove	*Mirt* wood-burning	*Gonziye* wood-burning	*Tikikil* wood-burning	*Lakech* charcoal-burning		
Aleta-W.	184	4	22	4	8	4	38	20.11
Boloso-S.	204	1	16	0	3	1	20	9.80
Cheha	134	0	19	8	7	0	34	25.37
Mirab-A.	77	5	18	6	4	13	41	52.56
Total	599	10	75	18	22	18	133	
Users (%)	99.0	1.65	12.4	2.98	3.64	2.98	22	

The four types of ICSs actively used in the study area are: *Mirt* stove (without chimney), *Gonziye* multi-purpose stove, and *Tikikil* and *Lakech* cooking stoves. Of the four types, 75 households were using *Mirt*, followed by *Tikikil* with 22 households, and *Gonziye* and *Lakech* with 18 households each. The relative high rate of uptake of *Mirt* stove could be attributed to two factors. First, *Mirt* is one of the earliest ICSs intervention projects in Ethiopia launched in 1991. Second, *Mirt* is an '*Injera'* baking stove with a longer lifespan (5 years on average) compared to others. Given that more than 50% of the household energy demand is used for '*Injera'* baking in Ethiopia (Mulugeta et al., 2017), *Mirt* stove with a potential fuel-saving of up to 50% (GIZ, 2011) is fairly attractive.

The results from the Pearson's chi square (χ^2) tests for independence of ICSs usage with respect to the four districts and household characteristics (Table 4) showed that ICSs use is strongly associated with the location of the household. Evidently, 52.6% of the households in Mirab-abaya district were found to be ICSs users while only 9.8% of the households in Boloso-sore use ICSs. The reason for the significant effect of location on ICS use could be that many families in Mirab-abaya and Aleta-wondo districts are cash-crop growers and hence could have the means to purchase ICSs. Conversely, in Boloso-sore district where many households have low income, use of ICSs is minimal.

Table 4. Pearson's chi square (χ^2) test of adoption of ICSs and household characteristics

Variable		n	ICS users (N =133)	Non-users (N=472)	χ2 stat	P - value
Gender	Male	509	110	399	0.25	0.610
	Female	96	23	73		
Location (district)	Aleta wondo	189	38	151	61.46***	0.000
	Boloso-sore	204	20	184		
	Cheha	134	34	100		
	Mirab-abaya	78	41	37		
Gross annual cash income class (ETB)	< 20,000	268	15	253	127.52***	0.000
	20,000 –40,000	123	22	101		
	40,000 –60,000	108	46	62		
	60,000 – 80,000	66	40	26		
	> 80,000	40	10	30		
Distance to wood source (round-trip)	< 20 min.	198	19	179	77.72***	0.001
	20 – 40 min.	143	27	116		
	40 – 60 min.	208	51	157		
	> 60 min.	56	36	20		

*** and ** represent statistically significant association at $p < 0.01$ and $p < 0.05$, respectively.

The strong influence of household income on ICSs use is also vivid from the results of the χ^2 test in Table 4 where more than 72% of the ICSs users have a gross annual cash income of ETB 40,000 and above. Another factor related to the geographic location was that the price of ICSs varies with distance to local ICSs production and retailing centres. As a result, in districts such as Mirab-abaya and Cheha where ICSs producers are in short distance to rural households, the price of ICSs was cheaper than in other districts, hence accelerating the use of ICSs. The distance between households' home and the main wood sources (local forest areas) was found to be strongly and negatively associated with the use of ICSs. More than 65% of the ICSs user households live within a round-trip walking distance of 40 minutes and above from the wood source (forest and woodland areas). This may necessitate the use of fuelwood-saving stoves as the access and availability of fuelwood declines with an increase in distance to the wood source.

On the other hand, almost all the households (99%) regardless of ICSs adoption were found using the traditional three-stone tripod for cooking, baking, or both. It was also found that out of the 133 ICSs users, 18 (13.5%) were using *Lakech* charcoal-burning stove along with the traditional open-fire tripod. However, since fuelwood is the most dominant fuel used in rural Ethiopia, subsequent analyses in this study have considered only those households who are utilizing one of the three commonly used wood-burning ICSs (*Mirt, Gonziye,* and *Tikikil)* for ease of comparative analysis of research variables. Therefore, ICS user (intervention group) in the following sections of this paper refers to the 115 ICS-users (75 *Mirt users*, 18 *Gonziye users,* and 22 *Tikikil* users) whereas the non-user (control group) refers to the 472 sample households who are solely dependent on the traditional stove for cooking and baking purposes.

4.3. Energy sources and consumption patterns of sample households

4.3.1. Household energy sources for cooking

Analysis of the primary energy sources of sample households for cooking and baking showed that the majority of both ICS users (86.47%) and non-users (91.95%) depend on fuelwood. Apart from fuelwood, crop residues are used as primary cooking fuels by 3.76% of ICS-users and 2.97% of non-users. Charcoal was reported as primary cooking fuel by 5.26% of ICSs users and 1.48% of non-users.

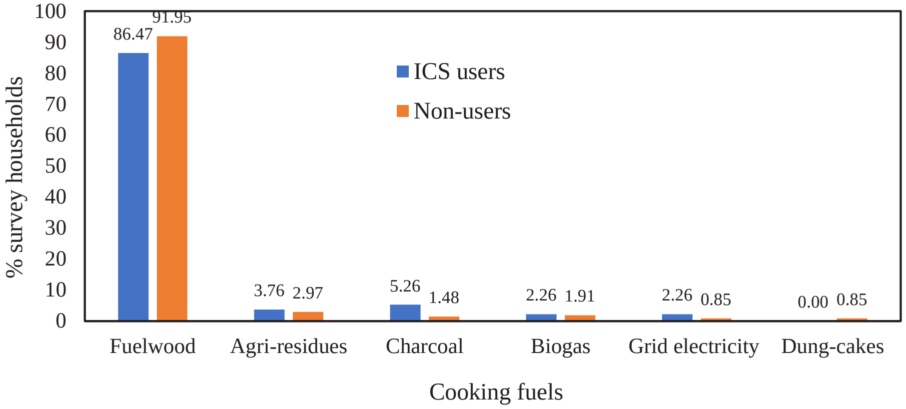

Fig 5. Primary cooking fuels of ICS user and non-user households

In contrast, the use of modern and clean energy sources such as electricity and biogas for cooking was generally limited. This is despite 32% of the sample households being connected to the national grid. The use of dung cakes and kerosene as primary cooking fuels was also negligible although these fuels are widely used in other parts of Ethiopia.

4.3.2. Household fuelwood consumptions of ICSs users and non-users

Before separately analysing the fuelwood savings and CO_2e emission reductions of each ICS, the key question was whether the fuel consumptions of ICSs users are significantly different from the non-users. For that, we compared the average consumptions of the 115 ICS- users against the 472 non-users for the main cooking fuels using Welch's t-test.

Table 5. Average fuel consumption quantities of ICS users and non-users

Variables	Stat	ICS-users (N=115)	Non-users (N=472)	Total samples (N = 605)	SE
Fuelwood collected from local forests kg/yr	Mean	2476.7	4181.5	4248.5***	3165.0
Fuelwood collected from own forest kg/yr	Mean	188.5	996.3	525.0**	695.4
Total fuelwood collected per HH, kg/yr	Mean	2665.2	5277.9	4773.5***	2734.0
Fuelwood purchased in kg/year	Mean	647.0	154.1	248.2***	844.7
Total fuelwood consumed/HH/year in kg	Mean	3313.6	5435.6	5021.8***	2692.0
Per capita fuelwood consumption in kg	Mean	623.4	984.2	913.8***	464.1
Agri. residue consumed/HH/year in kg	Mean	496.5	541.2	532.4	315.2
Charcoal consumed/HH/year in kg	Mean	93.5	68.1	73.3**	121.2
Dung-cakes consumed/HH/year in kg	Mean	9.1	19.2	17.4	35.5

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

The results showed that the average fuelwood consumption of an ICS- user household 3313.6 kg/year is significantly lower than a non-user 5435.6 kg/year. And the average fuelwood consumption per household for the total 605 samples was 5021.8 kg per year, and the average per capita fuelwood consumption was 913.8 kg/year. Likewise, the average consumption of agri-residues for ICSs users 496.5 kg/year is smaller than the consumption of non-users 541.2 kg/year but statistically insignificant. And, the average consumption of agri-residues for the total samples was 532.4 kg/ year. With respect to charcoal, we found that the average charcoal consumption of ICS users 93.56 kg/year is significantly higher than non-users 68.1 kg/year. Contrary to the fuelwood consumption pattern, the use of ICS is associated with an increase in charcoal consumption. This could be due to spill-over effects from urban charcoal users coupled with increased access to traditional charcoal-burning stoves in rural areas of Ethiopia including the SNNPRS. The quantity of dung-cakes consumed by ICS-users 9.1 kg/year is smaller than the quantity consumed by non-users 19.2 kg/year although the difference is insignificant.

4.3.3. Biserial correlation test between household ICSs use and fuel consumption

To further examine the (causal) relationship between household use of ICSs (1= user; 0= otherwise) and consumption of solid biomass fuels, biserial correlation coefficients (r_b) were computed following Kraemer (2006). The biserial correlation coefficient (r_b) is a special case of Pearson's correlation coefficient used to measure the relationship between two sets of variables X = {x_1, …, x_n} and Y = {y_1, …, yn} where one of the variables (Y) is artificially dichotomized {0, 1}. The results (see Table 6) showed that household fuelwood consumption is negatively and significantly associated with ICS use with r_b = - 0.62 at p-value = 0.000. This highlights that the significantly lower quantity of fuelwood consumed by ICS users compared with non-users (see Table 5) is highly likely due to the fuelwood saving effect of the use of improved cookstoves, *ceteris paribus*.

Table 6. Biserial correlation coefficients between ICSs use and fuel consumptions

Fuel consumptions	r_b coefficient	Lower 95.0% CL	Upper 95.0% CL	Z-stat	P-value
Fuelwood consumption (kg/yr)	–0.63	–0.69	–0.55	–13.90***	0.000
Agri residue consumption (kg/yr)	–0.04	–0.14	0.06	–0.79	0.426
Charcoal consumption (kg/yr)	0.41	0.32	0.49	8.42***	0.000
Dung cakes consumption (kg/yr)	–0.04	–0.14	0.06	–0.71	0.475

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

On the other hand, the correlation between ICSs use and agri- residues consumption, as well as, ICSs use and dung-cakes consumption were both negative but statistically weak. Yet, charcoal consumption is positively and significantly associated with household use of ICSs. As explained earlier, this is perhaps due to spill-over effects and increased access and use of (traditional) charcoal stove by ICS users. Given that the bulk of the household energy demand is met by fuelwood and the significant variations in mean consumption quantities for fuelwood and charcoal between ICS users and non-users, analysis of the effect of each improved stove in the following sections was carried out by comparing only the fuelwood and charcoal consumed.

4.4. Fuelwood savings from Mirt, Gonziye and Tikikil stoves

Since the average charcoal consumption of ICS users was significantly higher than the non-users, the charcoal consumption of both groups was converted into fuelwood by applying the FAO (2002) fuelwood to charcoal conversion factor from traditional kilns in East Africa. The fuelwood equivalent of charcoal consumed was then incorporated into the fuelwood consumptions for each group to estimate the aggregate consumptions. The statistical significance of net fuelwood savings from each stove per household per year was thence determined by using Welch's t-test for unequal sample sizes and/or unequal variances as presented in Tables 7 to 9.

Table 7. Fuelwood savings of *Mirt* stove users

Parameters	Mirt users (N= 75)	Non-users (N = 472)	Total Mean (N = 605)	SE	P–value
Per capita fuelwood consump/yr in kg	663.2	984.2	913.8**	623.6	0.036
Fuelwood consump/month in kg	295.0	452.9	187.9***	100.5	0.007
Fuelwood consump/yr in kg	3540.3	5435.6	5021.8***	3057.4	0.006
Charcoal consump/yr in kg	60.2	33.1	73.3**	144.5	0.044
Fuelwood equiv of charcoal/yr in kg	397.3	218.4	483.9	186.8	–
Total fuelwood consump/yr in kg	3937.6	5654.1	5505.7***	1016.8	0.000
Fuelwood savings/month in kg	143.0			57.5	
Fuelwood savings/yr in kg	1716.5			133.2	
% Fuelwood savings	30.3%				

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances
*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

Table 8. Fuelwood savings of Gonziye stove users

Parameters	Gonziye users (N= 18)	Non-users (N = 472)	Total Mean (N = 605)	SE	P–value
Per capita fuelwood consump/yr in kg	540.4	984.2	913.8**	623.6	0.025
Fuelwood consump/month in kg	263.0	452.9	187.9***	100.5	0.004
Fuelwood consump/ yr in kg	3156.9	5435.6	5021.8***	3057.4	0.005
Charcoal consump/ yr in kg	84.6	33.1	73.3**	144.5	0.033
Fuelwood equiv of charcoal/yr in kg	558.1	218.4	483.9	186.8	–
Total fuelwood consump/yr in kg	3715.0	5654.1	5505.7***	1016.8	0.000
Fuelwood savings/month in kg	161.6			69.0	
Fuelwood savings/yr in kg	1939.1			146.6	
% Fuelwood savings	34.3%				

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

Table 9. Fuelwood savings of Tikikil stove users

Parameters	Tikikil users (N= 22)	Non-users (N = 472)	Total Mean (N = 605)	SE	P–value
Per capita fuelwood consump/yr in kg	535.9	984.2	913.8**	623.6	0.019
Fuelwood consump/ month in kg	237.4	452.9	187.9***	100.5	0.000
Fuelwood consump/ yr in kg	2849.6	5435.6	5021.8***	3057.4	0.004
Charcoal consump/ yr in kg	109.3	33.1	73.33***	144.5	0.007
Fuelwood equiv of charcoal/yr in kg	721.5	218.4	483.9	186.81	–
Total fuelwood consump/yr in kg	3571.1	5654.1	5505.7***	1016.8	0.000
Fuelwood savings/month in kg	173.5			48.2	
Fuelwood savings/yr in kg	2083.0			184.5	
% Fuelwood savings	36.8%				

Statistical tool: Welch's t-test for unequal sample sizes and/or unequal variances

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

The results from the separate analysis of *Mirt*, *Gonziye,* and *Tikikil* stoves revealed that the average monthly fuelwood consumption of a *Mirt* stove user is 143 kg less than the traditional open-fire user. The average monthly fuelwood consumptions of *Gonziye* and *Tikikil* users was less by 161.6 kg and 173.5 kg respectively compared with traditional tripod users. Based on these results, the use of one *Mirt* stove could save 1716.5 kg of fuelwood, *Gonziye* 1939.1 kg, and *Tikikil* 2083.0 kg per household per year. This means that a household that had adopted a *Mirt* stove can reduce its fuelwood consumption by 30%, *Gonziye* user by 34%, and a Tikikil user by nearly 37% per year compared to the traditional stove user. An earlier study by Dresen et al. (2014) in Ethiopia had estimated that the use of one *Mirt* stove could save 1280 kg per household per year. Compared to this value, our estimates appear relatively higher. This could be owing to location-specific factors and differences in estimation methods.

Given that almost 85% of the fuelwood consumed per household is collected from 'open access' state and communal forests (see Table 5), the results imply that the contribution of ICSs in aiding the solution for the fuelwood crisis, and the associated deforestation and forest degradation for domestic energy use is significant. Assuming that 10 million of the 15 million ICSs disseminated in Ethiopia thus far (MEFCC, 2017) are currently functional, the fuelwood savings estimated above indicate that Ethiopia could avoid the consumption of between 17.16 and 20.83 million tons (Mt) of fuelwood per year by using ICSs (supposing the three ICSs are the most widely used). This means Ethiopia could decrease its annual biomass energy consumption of about 60 Mt per year (most of which is used for cooking and baking end-uses) (MoWIE, 2014) by 25% to 30% by utilizing ICSs. From a sustainable biomass utilization standpoint, the results signify that ICSs are viable options for reducing the over-exploitation of biomass fuels and balancing of the annual demand for fuelwood with the sustainable yield in Ethiopia and other parts of sub-Saharan Africa and the developing world at large.

4.5. CO_2e emission savings from Mirt, Gonziye and Tikikil stoves

Based on the fuelwood savings of each ICS estimated earlier (Tables 7 to 9); the potential CO_2e emissions avoided by each stove was calculated assuming the net calorific value of fuelwood (air-dried) at 15 MJ/kg (Hall et al., 1994) and emission intensity of 109.7 g CO_2e/MJ of fuelwood burned in traditional stoves (Bhattacharya and Salam, 2002; IPCC, 2006). The results (see Table 10) show that a single *Mirt* stove could avoid the emission of on average 2, 825 kgCO_2e/year. Following the same calculation method, the emission reduction of a single *Gonziye* and *Tikikil* stoves was estimated to be 3,191 kgCO_2e/year and 3,428 kgCO_2e/year respectively. The results show that compared to the traditional tripod, the three ICSs can reduce household CO_2e emissions significantly. The present results are relatively higher than the findings of Dresen et al. (2014) who estimated that a single *Mirt* stove in southern Ethiopia could avoid the emission 2,145 kgCO_2/year.

Table 10. Estimated annual CO_2e emissions savings from Mirt, Gonziye and Tikikil stoves

Parameters	Mirt (N = 75)	Gonziye (N= 18)	Tikikil (N = 22)	Mean	SE
Total fuelwood savings, kg/yr	1716.5	1939.1	2083.0	1912.8	184.6
Emission factor (kg CO_2e/kg of fuelwood in traditional stoves)	1.6455	1.6455	1.6455	1.6455	
Total emission savings, kg CO_2e/yr	2825	3191	3428	2997	303.8

Supposing that 10 million of the 15 million ICSs distributed in Ethiopia by 2017 (MEFCC, 2017) are currently functional, the results imply that Ethiopia could avoid the emission of 28 Mt – 34Mt of CO_2e per year from the use of ICSs. This amounts to 18 -22% reduction in the country's total GHGs emissions (150 Mt CO_2e/year (UNDP, 2011)). These findings suggest that beyond woodfuel savings, ICSs have substantial potential for abating CO_2e emissions, thereby assisting Ethiopia's low-carbon economic development path and the global GHGs emissions reduction effort. Moreover, the large CO_2e emission savings from these stoves indicate that if widespread dissemination and uninterrupted use of these stoves can be achieved, ICSs programs in Ethiopia and other developing countries could generate revenue from carbon credits for emission reductions under the United Nations Clean Development Mechanism (CDM) and other international Green Climate Funds.

4.6. Time savings from *Mirt*, *Gonziye,* and *Tikikil* stoves use

Among the potential benefits of ICS use is its effect on household fuelwood collection and cooking times. In view of this, the fuelwood collection, and cooking and baking time savings of each stove were estimated by using the data from the direct kitchen cooking studies and surveys. The results (see Table 11) show that *Mirt*, *Gonziye,* and *Tikikil* user households could save on average 1.12 hrs, 1.26 hrs, and 0.77 hrs per week respectively from reduced fuelwood collection. Likewise, the analysis for cooking and baking time savings indicated that *Mirt* stove (calculated per baking sessions and extrapolated to weekly basis) provides an average time savings of 0.18 hrs/week; *Gonziye* cooking and baking stove 0.74 hrs/week, and *Tikikil* cooking stove 1.03 hrs/week.

Table 11. Household times savings from fuelwood collection, cooking/baking

	Mirt			Gonziye			Tikikil		
Parameters	Non-users	Users	Saving	Non-users	Users	Saving	Non-users	Users	Saving
Time spent for wood collection/ week, hrs	6.53	6.41	1.12	7.11	5.85	1.26	7.60	6.83	0.77
Time spent for cooking/baking/ week, hrs	8.497	8.316	0.18	8.69	7.95	0.74	10.24	9.21	1.03
Total time savings/week, hrs			1.30			2.00			1.80
Aggregate total time savings/ HH/year, hrs			62.40			96.00			86.40

The higher time savings of *Gonziye* stove could be due, in large part, to the multi-purpose use (baking and cooking) of the stove. Whereas the relative higher time savings of *Tikikil* stove compared with *Mirt* is related to its frequent usage (2 times per day on average) compared with *Mirt* that is used 2.5 times per week. *Gonziye,* on the other hand, is used 3 times per week on average. Aggregating the fuelwood collection and cooking/baking time savings, it was estimated that a *Mirt* stove user could save 62.40 hrs, *Gonziye* user 96.00 hrs, and *Tikikil* user 86.40 hrs per year. This means that one *Mirt* stove could save 31 minutes per baking session, *Gonziye* 40 minutes per baking or cooking session, and *Tikikil* 7.8 minutes per cooking session. Overall, the results indicate that the use of *Mirt*, *Gonziye* and *Tikikil* stoves significantly lowers rural households' fuelwood consumption and CO_2e emissions. This reduces the deforestation and forest degradation from the high demand for woodfuels, thereby contributing to the sustainability of biomass utilization and mitigation of climate change. The fuelwood collection and cooking/baking time savings increase the time available for education and productive economic activities.

5. Cost-benefit analysis and estimation of economic benefits

The underlying justification for the CBA of ICSs essentially lies in the welfare economics rationale (Broadway and Bruce, 1984) that households choose to use ICSs to maximize their economic benefits and well-being. In this CBA, it is assumed that the values of most parameters remain constant in future years (lifespan of the stoves). Since most of the ICSs were in regular use, the utilization rate of 100% is assumed for all the ICSs.

5.1. Valuation of costs and benefits

The costs accounted for in the CBA were capital costs of the ICSs, transport, maintenance and other miscellaneous costs (see Table 12). A maintenance cost (plate replacement) of ETB 50 is assumed to occur every year for both *Mirt* and *Gonziye* stoves. Similarly, a maintenance cost of ETB 65 is assumed to occur every year for the *Tikikil* cooking stove. These maintenance costs are based on data from ICS users and researchers in the field. All other costs were accounted for in the initial year (Y=0). Valuation of costs related to the acquisition of the ICSs was made directly by using market prices in ETB.

Table 12. Summary of average adoption/use costs of the three ICSs in ETB in 2018

Cost Items	*Mirt*	*Gonziye*	*Tikikil*
Capital costs including transport (ETB)	180	80	200
Maintenance costs over economic lifespan (ETB)	250	100	195
Other miscellaneous costs (ETB)	15	10	25
Total (ETB)	445	190	420
Average lifespan (years)	5	2	3

The benefits accounted include household fuelwood collection and expenditure savings (B_{fs}), fuelwood collection, cooking and baking time savings (B_{cts}) and benefits from CO_2e emission reduction (B_{er}). As indicated in section 3.3.2, benefits due to better health (B_{bh}), preservation of forest cover (B_{pfc}), and improved soil fertility (B_{bsf}) were deduced and included. Valuation of benefits was made in two phases. In the first phase, since 647 kg (19.5%) of the total 3313.7 kg of fuelwood consumed by an ICS user is purchased from local markets (Table 5), valuation of 20% of the total fuelwood savings of each ICS was made by using market prices as an *avoided fuelwood purchase* (Tables 13 and 14). In the second phase, since 80% of the fuelwood consumed by an ICS- user is obtained from collection, valuation of benefits from *avoided fuelwood collection* was made in two steps. First, we created a shadow wage rate for the opportunity cost of labour spent on fuelwood collection from the local wage rate for unskilled daily labour.

Table 13. Average market price of fuelwood in the study areas in Eth. Birr in 2018

ICSs	Average market price of a human load of fuelwood in ETB	Average weight of a human load of fuelwood in kg	Price per kg of fuelwood in ETB
Aleta wondo	71.00	26.30	2.70
Cheha	65.50	23.54	3.04
Boloso-sore	63.89	25.50	2.50
Mirab-abaya	80.19	26.45	3.03
Total average	69.86	25.16	2.82

Following Atampugre (2014), the shadow wage rate of an hour spent by households on fuelwood collection was assumed worth 80% of the local wage rate for unskilled daily labour. The main reasoning for reducing the wage rate of fuelwood collectors by 20% compared to daily labourers is that most of the household members collecting fuelwood are women and children who may not have equal market demand for daily labour as the regular daily labourers. The average daily wage rate for an unskilled daily labourer in the study areas in 2018 was ETB 100, which is about ETB 12.5 per hour.

This means that an hour spent on fuelwood collection (80% worth of the 12.5 ETB) has a shadow wage rate of ETB 10. From this, in the second step, the shadow price of 1 kg of fuelwood collected by an ICSs user was estimated by using equation 6 as:

$$p = \left(\frac{\text{Average total hours spent for fuelwood collection per year by ICSs user}}{\text{Average total fuelwood collected per year by ICSs user}}\right) * 10\ ETB$$

$$p = \left(\frac{264.96}{2676}\right) * 10\ ETB \approx 1\ \text{ETB/kg}$$

Using this shadow price of 1 ETB/kg, the monetary value of *avoided fuelwood collections* (80% of the total savings) of ICSs users was estimated for each stove as shown in Table 14. In the same way, the monetary value of fuelwood collection and cooking time savings were calculated by using the estimated shadow price of labour (ETB 10/hr), and the results are shown in Table 15.

Table 14. Household monetary benefits from fuelwood savings in ETB in 2018

Benefits Item	*Mirt*	*Gonziye*	*Tikikil*
Total fuelwood savings	1716.53	1939.13	2083.03
Avoided fuel purchases in kg	343.31	387.83	416.61
Fuel purchase savings in ETB (P =2.82 ETB/kg)	968.13	1093.67	1174.83
Fuel collection savings in kg	1373.22	1551.30	1666.42
Monetary value of fuelwood collection savings (P= 1 ETB/kg)	1373.22	1551.30	1666.42
Total economic benefits of fuelwood savings/ ICSs/yr in ETB	2341.35	2644.98	2841.26

Table 15. Monetary benefits from fuelwood collection and cooking time savings

ICSs	Time savings /yr in Hrs	Daily wage rate for unskilled casual labour in ETB	Opportunity cost of labour/day (80% of labour wage)	Shadow wage of labour/Hr	Total monetary benefits
Mirt	62.40	100	80	10	624.00
Gonziye	96.00	100	80	10	960.00
Tikikil	86.40	100	80	10	864.00

To calculate the monetary benefits from CO_2e emission savings, the carbon auction price of the European Union's carbon Emission Allowances (EUA) in August 2018, i.e. average price of €18.75/tCO_2e was used and the results are presented in Table 16.

Table 16. Potential monetary benefits from CO_2e emission reductions in ETB

ICSs	Total CO_2e emission savings in ton/year	Price of 1 ton of CO_2e in August 2018 in Euro €	Price of 1 ton of CO_2e in 2018 in ETB	Total monetary benefits in ETB
Mirt	2.825	18.75	600.57	1696.61
Gonziye	3.191	18.75	600.57	1916.42
Tikikil	3.428	18.75	600.57	2058.75

*1€ =32.0302 ETB in August 2018

By applying the ratio (84.23%) of the sum of economic benefits from B_{fs} + B_{cts} +B_{er} in the total economic benefits as shown in Equation 2, the total economic benefits of each ICSs including the benefits due to B_{bh}, B_{pfc} and B_{bsf} were estimated and presented in Table 17.

Table 17. Summary of total economic benefits from ICSs in ETB in 2018

ICSs	Fuel savings	Time savings	CO_2e savings	Total benefits accounting only B_{fs}, B_{cts} and B_{er}	Benefits from B_{bh} + B_{pfc} + B_{bsf}	Total benefits including B_{bh} + B_{pfc} + B_{bsf}
Mirt	2341.35	624.00	1696.61	4661.96	874.81	5536.77
Gonziye	2644.98	960.00	1916.42	5521.40	1036.08	6557.48
Tikikil	2841.26	864.00	2058.75	5764.01	1081.61	6845.62

5.2. ICSs lifespan and discounting

The economic lifespan of the three ICSs was determined based on users' experience, and information from key informants, local stove producers, and GIZ-ECO (2010; 2011; 2014) reports. The average lifespan of *Mirt* stove was estimated at 5 years; *Gonziye* 2 years and *Tikikil* 3 years. The discount rate (real) used for the economic evaluation was based on the nominal interest rate of 15% payable by rural households in the study area on loans from local micro-credit finance institutions (Omo micro finance-Ethiopia). This interest rate was used after deducting the annual inflation rate of 9.85% in 2017 in Ethiopia (World Bank, 2017). Hence, the discounting of future costs and benefits to their present values was done by using a real interest rate of 5.15%.

5.3. Evaluation criteria and estimates

The evaluation criteria used to measure the total economic benefits and welfare effects of ICSs to the rural communities were the net present values (NPV), cost-benefit ratios (CBR), and internal rate of return (IRR). The net cash flows (discounted total costs and benefits over the lifespan of each stove) and estimates of the evaluation criteria for each stove are presented in Tables 18 and 19.

Table 18. Summary of Net Present Values (discounted Bt-Ct) of the ICSs

	0	1	2	3	4	5
Mirt	-195.00	4070.59	3101.64	2363.12	1800.28	1371.36
Gonziye	-90.00	4936.52	3767.74			
Tikikil	-225.00	5042.78	3840.60	2924.72		

Table 19. Estimates of economic efficiency/impact indicators of the ICSs

	NPV in ETB	NPV in USD	BCR	IRR (%)
Mirt	12 512.0	460.4	20.1	2064%
Gonziye	8 614.3	317.0	42.0	5460%
Tikikil	11 583.1	426.2	19.6	2217%

*1 USD = 27.1776 ETB in August 2018

The results from the CBA revealed that all three ICSs have positive NPV implying that all three ICSs can provide substantial net economic return to the rural community during their lifespan and investment in any of these stoves is economically efficient compared to the status quo (use of the traditional tripod). The results indicate that *Mirt* stove could provide a net economic benefit of ETB 12 512 (US$ 460) during its 5 years lifespan, *Gonziye* ETB 8 614 (US$ 317) during its two years lifespan and *Tikikil* ETB 11 583 (US$ 426) during its three years lifespan. Although these three ICSs are not used exactly for the same purpose, it appears that *Mirt* injera-baking and *Tikikil* cooking stoves provide higher net economic returns compared with *Gonziye* stove from the standpoint of NPV criterion. In retrospect, *Tikikil* and *Gonziye* had shown higher fuel and CO_2e emission savings than *Mirt* (Tables 7 to 9). However, the longer lifespan of *Mirt* has enabled it to provide the highest net economic benefits than the other two stoves.

The BCR ratio estimates showed that all the three ICSs have a BCR > 1, implying that the benefits derived from the utilization of the ICSs outweigh their costs (the stoves provide positive economic returns). *Gonziye* has the highest BCR of 42:1 implying that compared to the traditional open-fire tripod, the investment of one ETB in *Gonziye* yields a return of ETB 42. The BCR for *Mirt* and *Tikikil* were calculated at 20.1:1 and 19.6:1 respectively. All three ICSs have a very high IRR value indicating that the expected future annual rate of economic return on investment is many folds higher than the cost of capital (i.e. the stoves are highly profitable). Overall, the findings from the CBA indicate that the amount of economic gain and welfare benefit realized by using the ICSs is many folds higher than the cost entailed to acquire and operate them.

5.4. Reliability of data and instruments

To measure the scale of reliability of the data collected and the survey instruments used, we calculated Cronbach's alpha coefficients for internal consistency between eight key measurement variables (items) for the two groups (ICS users and non-users) separately. The alpha coefficients calculated were 0.78 for ICSs users and 0.72 for non-users. Since Cronbach's alpha coefficients > 0.7 indicate acceptable reliability (Taber, 2018), it can be concluded that both the data collected, and survey instruments used in this particular study were fairly reliable and reproduction of the study by subsequent independent studies can achieve the same result.

6. Conclusions and the way forward

The objective of this study was to analyse the potential fuel and CO_2e emission savings, and economic efficiencies of three improved biomass cookstoves (ICSs): *Mirt*, *Gonziye,* and *Tikikil* in rural Ethiopia based on data collected from a cross-sectional survey of 605 households and direct fuel consumption measurements of 48 samples. The study finds that compared to the traditional open-fire tripod, the use of a *Mirt* stove could lead to an average net fuelwood savings of 1.72 tons, *Gonziye* 1.94 tons, and *Tikikil* 2.08 tons per household per year. In terms of CO_2 emissions, our estimates showed that the use of one *Mirt* stove could avoid the emission of 2.82 tons, *Gonziye* 3.19 tons, and Tikikil 3.43 tons of CO_2e per year. The estimates for household fuelwood collection and cooking/baking time savings showed that compared to the traditional stove, a *Mirt* stove user could save a total of 62.4 hrs/year, *Gonziye* user 96.0 hrs/year and *Tikikil* user 86.4 hrs/year.

These results imply that, if 67% of the ICSs distributed in Ethiopia so far (10 million out of 15 million) are currently functional, the country could reduce its total biomass energy consumption by 25 to 30%; and its CO_2e emissions by 18- 22% per year by effectively applying ICS. The cost-benefit analysis indicated that all the three ICSs have positive and considerable Net Present Values implying that all three ICSs provide substantial net economic benefits compared to the status quo (use of traditional open-fire tripod stove). According to our estimates, *Mirt* stove could provide a net economic return of US$ 460, *Gonziye* US$ 317, and *Tikikil* US$ 426 during the 2 to 5 years lifespan of the stoves.

In nutshell, the evidence from this study has shown that the three ICSs (*Mirt, Gonziye, and Tikikil*) if regularly and effectively utilized have substantial potential for reducing household solid biomass fuel consumption, fuel collection and cooking times; and CO_2e emissions thus improving the well-being of the rural community. The benefits from the ICSs are of paramount significance especially to women and children, who traditionally are responsible for cooking and fuelwood collection in Ethiopia. In a country where scarcity of biomass energy has become a serious problem, the significant fuel savings from the use of these ICSs mean a substantial aid to reducing deforestation and forest degradation from overexploitation of biomass fuels. This improves the conservation of forests and woodlands and the valuable ecosystem services they provide. Given that most of the wood consumed for domestic energy in Ethiopia and sub-Saharan Africa is collected from 'open access' state and communal forests, the results imply that ICSs are viable options and essential component of the strategy for improving the sustainability of biomass utilization, balancing of demand for fuelwood with the sustainable yield, and mitigation of climate change. The implication is that Ethiopia and other biomass-energy dependent developing countries need to promote the large-scale and sustained use of ICSs through providing financial and non-financial incentives, and soliciting funds for certified emission reductions from ICSs in international carbon markets.

Notwithstanding the significant positive effects found, sustaining the energy, economic and environmental benefits from the use of ICSs in Ethiopia faces some major challenges that need to be addressed thoroughly. In view of that, the study recommends:

- Provision of adequate funding, technical and logistical support to ICSs promotion and dissemination projects including soliciting of carbon funding opportunities for reduced emissions from ICSs
- Provision of financial incentives, working capital, soft loans, and capacity building training to small-scale private ICSs producers, distributors, and potteries
- Implementation of well-crafted and locally fit ICSs promotion activities
- Market segmentation of ICSs to achieve economy of scale from the large demand with a small margin of profit for local producers without increasing the price of ICSs
- Building the research and product development capabilities of regional institutions in testing and evaluation of stoves for improved designs with greater efficiencies

7. References

Adkins, E., …, Modi, V. (2010). Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. Energy for Sustainable Development, 14:172–185.

Atampugre, G. (2014). Cost and Benefit Analysis of the adoption of Soil and Water Conservation methods in Kenya. Int J of Scientific and Research Publications, 4(8).

Bailis, R., ..., Smith, K.R. (2007). Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project. Energy for Sustainable Development, 11(2): 57-70.

Bensch, G., Peters, J. (2015). The intensive margin of technology adoption—Experimental evidence on improved cooking stoves in rural Senegal. J. Health Econ, 42: 44–63.

Beyene, A.D., ..., Vieider, F. (2015). Do Improved Biomass Cookstoves Reduce Fuelwood Consumption and Carbon Emissions? Evidence from Rural Ethiopia Using a Randomized Treatment Trial with Electronic Monitoring. Policy Research Working Paper No 7324, The World Bank.

Beyene, A.D., Koch, S.F. (2013). Clean fuel-saving technology adoption in urban Ethiopia. Energy Economics, 36: 605-613.

Bhattacharya, S.C., Salam, P.A. (2002). Low greenhouse gas biomass options for cooking in the developing countries. Biomass and Bioenergy, 22: 305 – 317.

Broadway, R.W., Bruce, N. (1984). Welfare Economics: Theory and Applications, Oxford: Basil Blackwell.

Brooks, N., ..., Pattanayak, S.K. (2016). How much do alternative cookstoves reduce biomass fuel use? Evidence from North India. Resource Energy Econ, 43:153–171.

Cochran, W.G. (1977). Sampling Techniques, Wiley, New York.

CSA. (2013). Federal Democratic Republic of Ethiopia, Central Statistical Agency. Population Projection for All Regions from 2014 – 2017, Addis Ababa. https://www.academia.edu/30252151/Federal_Democratic_Republic_of_Ethiopia_Central_Statistical_Agency_Population_Projection_of_Ethiopia_for_All_Regions_At_Wereda_Level_from_2014_2017(Accessed 03.03.19).

Dresen, E., ..., Müller, R. (2014). Fuelwood Savings and Carbon Emission Reductions by the Use of Improved Cooking Stoves in an Afromontane Forest, Ethiopia. Land 3(3):1137-1157

EFAP. (1994). Ethiopian Forestry Action Program (EFAP): Final report Vol. II- The Challenges of Development: Ministry of Natural Resources Development and Environment Protection, Addis Ababa.

Eshetu, A.A. (2014). Factors Affecting the Adoption of Fuel-Efficient Stoves among Rural Households in Borena Woreda: North central Ethiopia. Int J of Energy Science. 4 (5).

European Emission Allowances (EUA). (2018). Price in EUR/tCO₂e 2018. https://www.eex.com/en/market-data/environmental-markets/spot-market/european-emission-allowances#!/2018/08/01 (Accessed 18.08.19)

FAO. (2002). Charcoal production and use in Africa: what future? Unasylva. No 211 *(53.)* FAO, Rome.

Foell, W., Pachauri, S., Spreng, D., Zerriffi, H. (2011). Household cooking fuels and technologies in developing economies. Energy Policy, 39: 7487–7496.

García-Frapolli, E., ..., Masera, O. (2010). Beyond fuelwood savings: valuing the economic benefits of introducing improved biomass cookstoves in the Purépecha region of Mexico**.** Ecol Econ., 69: 2598-2605.

Gebreegziabher, Z., ..., Toman, M.A. (2018). Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia. Resource and Energy Economics, 52:173-185.

Gebreegziabher, Z. (2007). Household Fuel Consumption and Resource Use in Rural-Urban Ethiopia. PhD Thesis Wageningen University. https://library.wur.nl/WebQuery/wurpubs/fulltext/31629 (Accessed 02.05.19).

GIZ-ECO. (2010). Sun Energy Project. Water Boiling Test Results for Institutional Rocket and Tikikil Stoves. http://library.uniteddiversity.coop/Energy/Biofuels/Stoves/WBT_results_CIRS%2BIRS%2BDelux%2BDoubleSkirt.pdf (Accessed 05.01.19).

GIZ-ECO. (2011). Bioenergy, GIZ Training manual for 'Mirt' stove. Energy Coordination Office. https://energypedia.info/wiki/File:Giz_Trainning_Manual_Mirt_stove_081211.pdf (Accessed 12.03.19).

GIZ-ECO. (2014). Stove Testing Result. A Report on Controlled Cooking Test of Gonziye Stove. https://energypedia.info/wiki/File:Giz_Trainning_Manual_Mirt_stove_081211.pdf (Accessed 12.04.19).

GIZ-HERA. (2018). Cooking energy compendium. A practical guidebook for implementers of cooking energy interventions. https://energypedia.info/wiki/Testing_of_Woodfuel_Stoves (Accessed 1.4. 19).

Global Alliance for Clean Cookstoves. (2012). Enhancing Markets for Delivery of Improved Cookstove Development and Promotion Support in Ethiopia-Market Analysis Report 2012. https://www.cleancookingalliance.org/binary-data/RESOURCE/file/000/000/160-1.pdf (Accessed 30.01.19).

Guta, D.D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. Energy Policy, 75: 217-227.

Habermehl, H. (1999). The Economics of Improved Stoves. Guide to micro- and macroeconomic analysis and data assessment. 2nd edition. German Agency of Technical Cooperation (GTZ), Eschborn, Germany.

Habermehl, H. (2007). Economic Evaluation of the Improved Household Cooking Stove Dissemination Program in Uganda. GTZ, Household Energy Program. http://www.hedon.info/docs/CostBenefitsUganda-v02.pdf (Accessed 22. 01.19).

Haile, K., Sandewall, M., Urgessa, K. (2009). Woodfuel demand and sustainability of supply in south-western Ethiopia, Case of Jimma Town. Research J. of Forestry, 3(2): 29-42.

Hall, D. O., Rosillo-Calle, F., Woods, J. (1994). Biomass utilization in households and industry—Energy use and development. Chemosphere, 29: 1099–1119.

IEA. (2018a). World Energy Outlook 2018. International Energy Agency, IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2018 (Accessed 12.5. 19).

IEA. (2018b). Energy statistics Ethiopia 1990 – 2016. International Energy Agency https://www.iea.org/statistics/?country=ETHIOPIA&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES (Accessed 28.03.19).

IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2.2—Stationary Combustion. Intergovernmental Panel on Climate Change http://www. ipcc-nggip.iges.or.jp/public/2006gl/vol2.html (Accessed 20.05.19).

Jeuland, M.A., Pattanayak, S.K. (2012). Benefits and Costs of Improved Cookstoves: Assessing the Implications of Variability in Health, Forest and Climate Impacts. PLoS One 7(2).

Kraemer, H.C. (2006). Correlation coefficients in medical research: from product moment correlation to the odds ratio. Stat Methods Med Res., 15(6): 525-45.

Legesse, W., Derese, A., Samuel, T. (2015). Determinants of Adoption of Improved Stove Technology in Dendi district, West Shoa, Oromia Regional State, Ethiopia. American Journal of Human Ecology, 4(4).

MacCarty, N., Still, D., Ogle, D. (20109. Fuel Use and Emissions Performance of Fifty Cooking Stoves in the Laboratory and Related Benchmarks of Performance. Energy for Sustainable Development, 14:161–171.

MEFCC. (2017). Federal Democratic Republic of Ethiopia; Ministry of Environment, Forest and Climate Change. Proposal for REDD+ investment in Ethiopia. http://www.mofed.gov.et/documents/10182/32227/REDD%2B+Investment++Plan_program+document.pdf/c39b22eb-abfc-48be-907c-b44ff4505e55 (Accessed 03. 02. 18).

Megen Power. (2008). Impact Assessment of Mirt Improved Biomass Injera Stoves Commercialization, Final Report submitted to MoARD/GTZ SUN Energy Programme, Addis Ababa. https://energypedia.info/images/c/c5/Mirt_impact_assessment_rpt_final.pdf (Accessed 07.05.19).

Mondal, A.H., ..., Rosegrant, M. (2018). Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. Energy, 149: 161-172.

MoWIE . (2014). Federal Democratic Republic of Ethiopia; Ministry of Water, Irrigation and Energy (MoWIE). National Biomass Energy Strategy for Ethiopia. Addis Ababa. http://www.euei-pdf.org/sites/default/files/field_publication_file/Ethiopia_Biomass_Energy_Strategy_and_Action_Plan_Final_2014_02_06.pdf (Accessed 13.06. 18).

Mulugeta, B., Tekestebirhan, D., Demissie, S.W. (2017). Optimization and CFD Simulation of Improved Biogas Burner for 'Injera' Baking in Ethiopia. Int J of Engineering Research & Technology, 6(1).

Mwampamba, T.H. (2007). Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. Energy Policy. 35, 4221-34.

Ndegwa, G.M., ..., Anhuf, D. (2016). Charcoal production through selective logging leads to degradation of dry woodlands: a case study from Mutomo District, Kenya. J Arid Land, 8: 618–31.

Obiri, B.D., ..., Marfo, E. (2014). The Charcoal Industry in Ghana: An Alternative Livelihood Option for Displaced Illegal Chainsaw Lumber Producers. Tropenbos International, Wageningen, The Netherlands.

Pearce, D., Atkinson, G., Mourato, S. (2006). Cost-benefit analysis and the environment: recent developments. Organisation for Economic Co-operation and Development, Paris. http://eprints.lse.ac.uk/id/eprint/2867 (Accessed 01.04.19).

Pine, K., ..., Riojas-Rodriguez, H. (20119. Adoption and use of improved biomass stoves in Rural Mexico. Energy Sustain. Dev., 15:176–183.

Putti, V. R., Tsan, M., Mehta, S., Kammila, S. (20159. The State of the Global Clean and Improved Cooking Sector. ESMAP Technical Paper No. 007/15. World Bank.

Shanko, M., Lakew, H., MEGEN_Power_Plc. (2011). Final Report: Household Energy Baseline Survey in SNNPR; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ): Addis Ababa, Ethiopia.

Schlesinger, W.H. (1991). Biogeochemistry, an Analysis of Global Change. New York, Academic Press.

Taber, K.S. (2018). The Use of Cronbach's Alpha When Developing and Reporting Research Instruments in Science Education. Res Sci Educ, 48: 1273–1296.

Thomas, E., ..., Foster, C. (2015). Improved stove interventions to reduce household air pollution in low and middle-income countries: a descriptive systematic review. BMC Public Health, 15(60).

Wathore, R., Mortimer, K., Grieshop, A.P. (20179) In-Use Emissions and Estimated Impacts of Traditional, Natural- and Forced-Draft Cookstoves in Rural Malawi. Environ Sci Technol, 7; 51(3): 1929–1938.

World Bank. (2017). Inflation, consumers prices (annual %), Ethiopia. https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?locations=ET (Accessed 30.05.19).

UNDP Ethiopia. (2011). Framework for UNDP Ethiopia's Climate Change, Environment, and Disaster Risk Management Portfolio. https://www.et.undp.org/content/ethiopia/en/home/library/environment_energy/publication_1.html (Accessed 12.05.19).

Appendix I: Sensitivity analysis

In order to test the robustness of the results of the cost-benefit analysis to potential uncertainties and assumptions, a partial sensitivity analysis was carried out taking two of the most important uncertainty variables: the discount rate and the price (cost) of ICSs. As shown in Figure 6, the NPV of the three ICSs are generally elastic to changes in the price of the stoves. As such, even a 100% increase in the price of the stoves will have little effect on the net economic benefits (NPV) of each ICSs. In contrast, the NPV of the three improved stoves, particularly that of *Mirt* and *Gonziye* is considerably sensitive to changes in the discounting rate as manifested in the steadily declining NPV following increase in discounting rates.

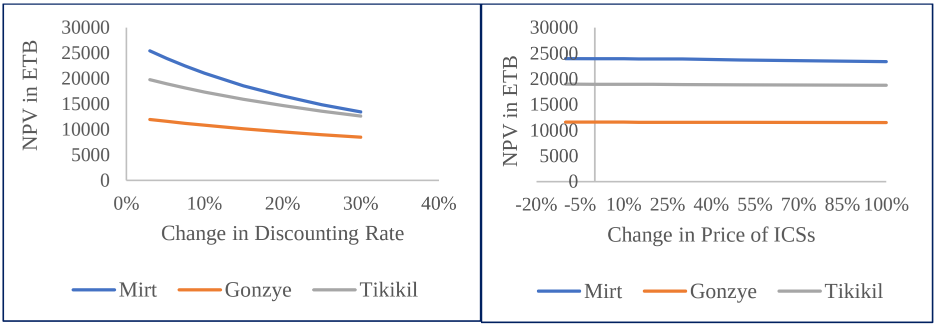

Fig. 6. Sensitivity of NPV of the ICSs against changes in the price of stove and discounting rate

Overall, the results from the partial sensitivity analysis indicate that the net economic benefits accruing to the community from adopting ICSs will remain high given potential uncertainties in the price (cost) of the stoves and the discounting rates. The findings also hint that the results of the CBA are fairly robust to uncertain parameters and can be used as indicators of current and future economic efficiencies of these ICSs in the SNNPRS and rural Ethiopia at large.

Paper IV

Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from southern Ethiopia

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Abstract

Lack of access to electricity is one of the major impediments to economic development and the provision of public services in rural areas of developing countries. This study examines the impacts and challenges of rural electrification with Solar Photovoltaic (PV) systems in southern Ethiopia from a survey of 605 sample households and direct field investigation of 137 solar PVs/lanterns. The study finds that the use of stand-alone solar PV systems in rural Ethiopia is growing and its impact is considerable. A solar-electrified rural household consumes on average 43.68 litres less kerosene and emits 107 kg less CO_2 per year compared with a non-electrified household. This reduction in kerosene use and the access to electricity from solar PVs could enable a rural household to save ETB 1765 to 2005 (US$ 65 to $75) per year from avoided energy costs and mobile charging expenses. The results showed that Solar PV systems provide rural families with access to basic electricity for 3 to 5 hours a day, reduce their health risks from kerosene lamps; extend their workdays into the evenings, and allow micro-businesses to generate more income. These findings demonstrate that solar PVs systems have substantial potential to improve the electricity access, socio-economic, and health conditions of rural families while reducing household level CO_2 emissions. Tapping this potential however requires tackling the major challenges facing the sustainability and efficient use of solar products from poor quality products in the market, high cost of quality-verified products, lack of after-sales maintenance services, and limited access to credit financing sources.

Keywords: Rural electrification, solar PV systems, kerosene consumption, energy substitution, energy costs, CO_2 emission, income generation

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1. Introduction

Ethiopia has been experiencing strong economic growth in recent years averaging 9.9% per year between 2008 and 2018 (WorldBank, 2019a). This rapid economic expansion coupled with spurring population growth has led to a dramatic increase in demand for energy, with demand for electricity forecasted to grow by 10.1-14.2% per year between 2012 and 2037 (EEP, 2014). To overcome this challenge, Ethiopia has been striving to expand its power generation capacity in recent years. Yet, Ethiopia remains amongst the sub-Saharan African countries with the lowest rate of access to modern energy services. In rural areas where most of Ethiopia's population lives, electricity coverage was 31% in 2017 (World Bank, 2019b). As a result, kerosene and kerosene wick lamps remain the primary lighting energy sources of most rural and off-grid communities in Ethiopia. So much that, Ethiopia ranks second only to Nigeria in kerosene consumption for lighting in Africa with an average import of 295 million litres of kerosene per year spending over ETB 2.9 billion (US$ 177 million) (Lighting Africa, 2012; Tedsen, 2013). What is more, the black carbon (BC) emitted from the traditional kerosene wick- lamps causes indoor pollution with grave health consequences (Lam et al., 2012a).

One of the biggest challenges for ensuring universal electricity supply in rural Ethiopia is the massive capital investment required to develop and expand grid infrastructures to off-grid (rural and remote) areas. For the bulk of Ethiopia's population lives in widely dispersed rural villages, studies have shown that providing conventional grid-electricity to most rural households is currently a costly undertaking for Ethiopia (Ecofys, 2016). Even when Ethiopia's grand national electrification program is completed, only about 65% of the total population will have access to electricity by 2025. This means that the remaining 35% (more than 12 million households mainly in rural/off-grid areas) will still be living without electricity and could thus benefit from an off-grid solution while waiting for the grid expansion (Lakew et al., 2011; Lighting Africa, 2019). With rapid fall in the cost of solar panels and average solar irradiation of 5.5 kWh/m^2/day (Lemma, 2014) in Ethiopia, this makes decentralized stand-alone solar PV systems viable, cost-effective and eco-friendly solutions for providing access to affordable electricity supply and clean lighting energy in rural and off-grid locations of Ethiopia.

In view of this, the government of Ethiopia has been promoting the distribution and use of stand-alone solar PV systems as an integral part of the national energy development strategy since 2010. As such, the Ministry of Water, Irrigation, and Electricity (MoWIE) in partnership with the private sector and international organizations has disseminated a large number of Solar Home Systems (SHS), Pico-PVs (lanterns) and institutional PV systems to rural/off-grid areas of the country (FDRE, 2016). According to IEA's (2012) simple classification, solar PicoPVs are solar products with PV panel power generation capacity of up to 10 Wp (watt peak); while SHSs have PV capacity of 10Wp to 200 Wp, and institutional PV systems have power generation capacity over 200Wp.

Amongst the main partners of solar electrification in Ethiopia include the Power Africa initiative; World Bank group's 'Scaling Solar' program, Solar Energy Foundation (SEF), Solar Lighting in Rural Ethiopia, and GIZ's Energising Development (EnDev). In 2013, the Ethiopian government passed the 'Energy Proclamation No 810/2013' that targets the proliferation of independent power purchase agreements (PPAs) and development of off-grid systems and efficient on-grid management practices. In 2018, the government passed the Public-Private Partnership (PPP) Proclamation No 1076/2018. These policies and proclamations are aimed at encouraging the participation of the private sector and investment in the country's energy sector development (SolarPlaza, 2019).

In the light of these multilateral efforts, reports from the government of Ethiopia and its international partners indicate that solar PVs have improved the access to electricity of un(der)-electrified households, and small businesses while reducing the adverse health and environmental effects of kerosene use (Lakew et al., 2017; Ecofys, 2016). According to Admasu (2011), solar electrified grocery owners in Rema rural village of North West Ethiopia were able to use solar electricity for refrigeration and TV thus improving their income. Moreover, these reports indicate that solar -electrified public health posts and schools have been able to provide much safer child delivery and improved quality of education (Admasu, 2011). Findings from a few published studies also suggest that the use of solar PVs systems in rural Ethiopia is gaining ground as a cost-effective solution to meet the basic electricity needs of households while improving the education and health of rural families (Müggenburg et al., 2012).

Notwithstanding the above positive accounts from the government and NGOs involved in solar technologies promotion; comprehensive investigations and empirical analysis on the actual impacts of solar PV systems on rural households' energy use and economic development based on real-time datasets are hardly available. The few studies carried out thus far have mainly focused on the diffusion of solar technologies (e.g. Kebede and Mitsufuji, 2017, 2014; Müggenburg et al., 2012). Other studies have dealt with the techno-economic feasibility of solar PV-wind/diesel, solar PV-grid, and solar PV-micro-hydro hybrid energy systems (e.g. Kebede, 2015; Giday, 2014; Bekele and Boneya, 2012; Bekele and Tadesse, 2012; Bekele and Palm, 2010).

As a result, little is known about the current state of use, distribution patterns, and actual impacts of SHSs and lanterns on the rural household's access to electricity, kerosene consumption, greenhouse gases (GHGs) emission, income generation activities, health care, and overall socio-economic development. Neither are the major determinants and barriers to the effectiveness and sustainability of solar-based electrification in the rural Ethiopian context fully understood. The main aims of this study were therefore to assess and empirically analyse the current uptake, use, and impacts of solar PV/PicoPV systems on rural households' access to modern energy and its economic and environmental co-benefits, as well as to examine the determinants and barriers to the widespread use and sustainability of solar technologies in rural southern Ethiopia.

2. Overview of rural electrification with solar PVs in developing countries

Several studies have indicated that decentralized stand-alone solar PVs systems offer a cost-effective and viable option for off-grid electrification in the developing world. For instance, a study by Urmee and Harries (2011) in rural Bangladesh reported that 92% of SHS users were able to access quality and reliable lighting from the SHSs. Similarly, evaluating GIZ's (German Development Agency) solar electrification project in Uganda, Harsdorff and Bamanyaki (2009) reported that 22% of SHS user micro-enterprises were able to get reliable lighting services from SHSs. While some authors argue that there is little evidence of direct economic impact (increase in income-generation) of households following solar PVs adoption (Feron, 2016; Wamukonya and Davis, 2001); others have counter-wise documented that households and micro-enterprises have been able to generate more income following the adoption of SHSs (Mondal and Klein, 2011; Obeng and Evers, 2010; Wijayatunga and Attalage, 2005).

For instance, a study by Obeng and Evers (2010) in Ghana indicated that rural micro-enterprises were able to generate additional income of US$5 -12 a day from grocery stores thanks to solar PV lighting. According to these authors, the average incomes of solar-electrified enterprises were 82% higher than non-electrified ones. Along the same line, Lighting Africa (World Bank, 2010) reported that replacing kerosene lamps with solar lights offers returns on investment of 15-45 times the cost of the solar lights. A UNEP (2013) assessment in Nigeria indicated that if Nigeria replaces all of the kerosene, candles, and dry-cell batteries used annually for off-grid lighting with solar lights, the country can save US$ 1.4 billion annually, an equivalent of 17.3 million barrels of crude oil. In Uganda, Harsdorff and Bamanyaki (2009) found that SHS-electrified households spent 74% less on energy expenses than non-electrified households.

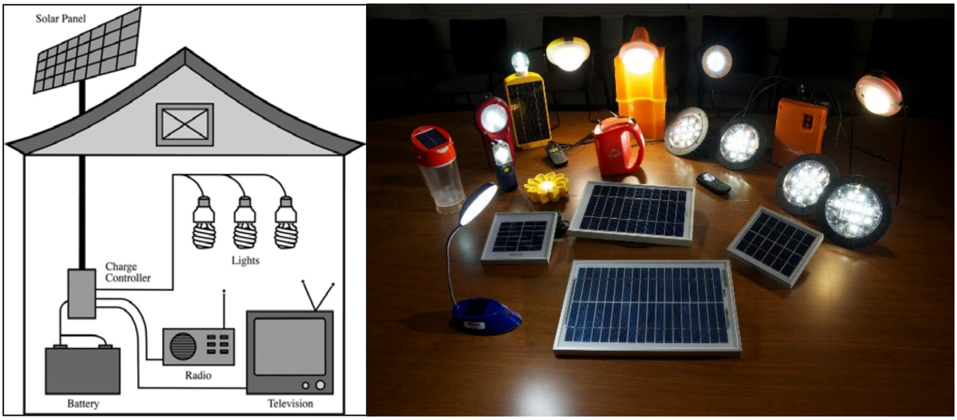

Figure 1. A typical SHS and selection of off-grid solar products in Ethiopia (Sources: Rebane and Barham, 2011; Lighting Global/Africa, 2018)

Furthermore, a study in five African countries (Kenya, Tanzania, Zambia, Malawi, and Senegal) by SolarAid (2014) showed that after purchasing solar PicoPV light, families reduced their kerosene consumption on average by 77% with average savings of 4.1 litres of kerosene per household per month. This reduction in kerosene consumption equates to financial savings of US$ 60 – $70 and emissions avoidance of 123 kg CO_2 per household per year. However, Mondal and Klein (2011) underscore that the direct economic impact of SHS is more realistic if only solar user households make use of the solar PVs for operating small businesses in addition to the lighting services.

Studies also suggest that solar PV systems provide considerable benefits in improving the health, education, environmental conditions and overall welfare of rural households. For instance, a study by Kudo et al. (2015) in Bangladesh showed that children in solar user families were exposed to air pollution and related eye irritations for significantly fewer hours than those in traditional kerosene lamp users. The authors reported that study hours among school children with solar lights were longer compared to non-solar users. A similar study in rural India (Buragohain, 2012) reported that 53 -69 % of solar user households noticed an improvement in their children's educational outcomes, and 37 -78% reported improvement in their living standards including a substantial decline in crime rates because of the availability of solar streetlights in the village. Investigating the association between access to solar light and education in rural Kenya, Hassan and Lucchino (2016) reported that access to lights through solar lamps was positively and significantly associated with an improved performance of children in education.

Regarding the environmental benefits of solar PV systems, studies show that switching to solar lighting from the traditional kerosene plays significant positive impacts on the environment and climate change mitigation through reducing emissions of CO_2 and BC. Keane (2014) cites that one traditional kerosene wick lamp emits up to 200 kg of CO_2 a year. This means that with a solar PV/light, households can reduce or even eliminate the use of kerosene lamps, thereby reducing CO_2 emissions and benefiting the environment. For instance, Brossman (2013) in Bangladesh found that SHS user households reduced their CO_2 emissions by 95.3 kg/year, while PicoPV (lantern) users were able to reduce their CO_2 emissions by 68.3 kg/year. Harsdorff and Bamanyaki (2009) in Uganda reported that the average kerosene consumption of SHS user households dropped from 3.5 litres to 2 litres per month following the adoption of SHSs.

Likewise, a study by Wang et al. (2011) in rural Bangladesh reported that access to SHSs displaced household kerosene consumption on average by 2.7 L/month. Using a carbon emission factor of 2.45 kg CO_2 per litre of kerosene burned, the authors estimated that the emission of 76 kg of CO_2 is avoided per year from a commonly used SHS (40-50 Wp). Whilst these studies generally highlight the substantial role of solar lighting systems in fulfilling the basic electricity needs and improving the health, education, and welfare of rural households in many parts of the developing world; the socio-economic, energy and environmental impacts of rural electrification with solar PV/PicoPv systems and the associated barriers in rural Ethiopia remains poorly investigated.

3. Materials and Methods

3.1. Study areas and sampling

This study was carried out in four rural districts, which are Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya (Figure 2), of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia. The SNNPRS lies between Latitudes 4°43' – 8°58' N and Longitudes 34°88' – 39°14' E**.** The region is composed of 14 administrative zones (provinces) and 4 special *woredas* (districts), consisting of a total of 137 rural districts and 22 urban administrations (CSA, 2013)**.** The districts are further sub-divided into *kebeles* (cluster of neighbourhoods), the smallest administrative units of Ethiopia. The total population of the SNNPRS was estimated to be 19. 2 million in 2017, of which about 90% are rural inhabitants composed of 2,743,502 households in 3,709 *kebeles* and 10% are urban residents composed of 367,493 households in 324 *kebeles* (CSA, 2013).

A multi-stage stratified random sampling was employed to select sample districts and households for the study. In the first stage, 23 rural districts (from the total of 137 rural districts), where renewable energy technologies interventions have been active over the last decade were identified based on data from the Central Statistical Agency (2013) and the SNNPRS Mines and Energy Agency. This was essential for the study to represent the mainstream technology intervention rural districts. The 23 selected districts were then clustered into three categories as highland, midland and lowland based on their agro-ecological conditions. The main purpose of clustering the rural districts into these agro-ecological zones is to examine potential effects of agro-ecology dependent factors on the adoption, accessibility and usage of solar technologies. Subsequently, two districts from the highland, one from the midland and one from the lowland were randomly selected by using a simple lottery method. Two districts were selected from the highland stratum because more than 50% of the 23 rural districts identified fell in this category.

Accordingly, Aleta-wondo and Cheha districts with a mean altitude of 2037 and 2130 meters above sea level (m.a.s.l.) respectively were selected from the highland category; whereas Boloso-sore with a mean altitude of 1877 m.a.s.l and Mirab-abaya with a mean altitude of 1193 m.a.s.l. were selected from the midland and lowland strata, respectively.

The total estimated population of Aleta-wondo district in 2017 was 187,957 comprised of 33, 738 households; and that of Cheha was 122,770 composed of 24,554 households (CSA, 2013). The total population of Boloso-sore district in 2017 was estimated to be 187,558 made up of 36,410 households and that of Mirab-abaya was 90, 508 composed of 12,784 households (CSA, 2013).

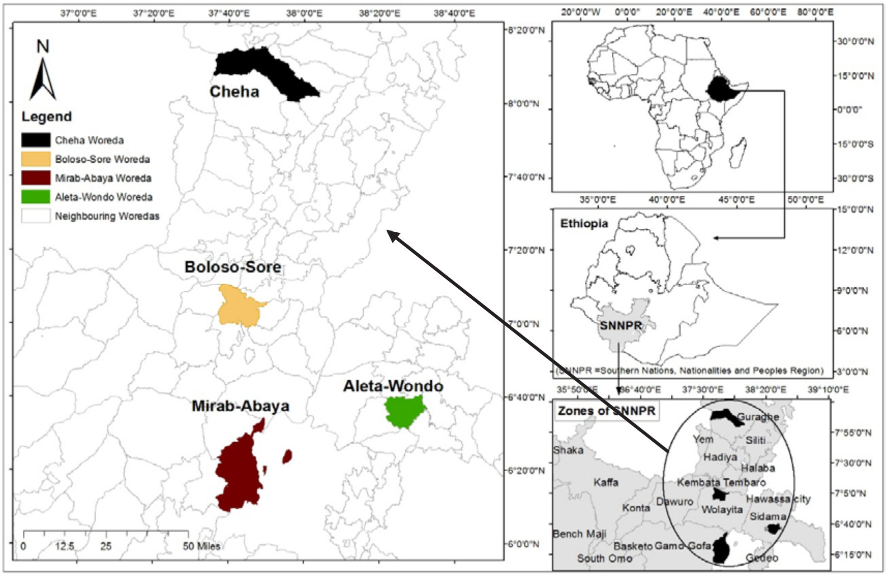

Figure 2. Location map of the SNNPRS region and the study districts (*woredas*)

In the second stage, a representative sample size for the study was determined at 95% confidence level, 4% precision (for smaller allowable error between sample estimates and true population values) and p = 0.5 (for unknown population proportion to generate the most conservative/largest sample size) following Cochran (1977) as:

$$N = \frac{(z^2\alpha/_2)\ (p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\ .\ (0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:

N= is the desired sample size

P = 0.5 is the assumed population proportion expected to have access to renewables

e= 0.04 is the desired precision (or margin of error) at 4%

$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size was estimated at 660. This total sample size determined was then distributed to the four study districts by using the probability proportional to the household size (PHS) method. Hence, out of the total sample sizes; 207 were allotted to Aleta-wondo, 224 to Boloso-sore, 151 to Cheha and 78 to Mirab-abaya districts. In the third stage, three *Kebeles* (cluster of neighbourhoods) were randomly chosen in each district and the sample size allotted to each study district was distributed to the three *kebeles* by using the same PHS method. Finally, individual sample households were randomly chosen from a complete list of all households in each of the *Kebeles* selected for the detailed study. List of all households in each *Kebele* was obtained from the local *Kebele* administrations.

3.2. Data sources and collection methods

3.2.1. Household surveys

Primary data for the study were collected from direct field assessments, cross-sectional household surveys and key informant interviews. Prior to the actual survey, preliminary studies were carried out in the four selected districts, and information was gathered on various characteristics of the population, lighting energy use, types of solar products, geographic distribution patterns, and supply sources including applications of the solar technologies. This was accompanied by careful designing of survey instruments (semi-structured questionnaires) and field data collection formats based on the information collected from the preliminary studies, the objective of the study, and review of relevant literature. Subsequently, four data enumerators were hired for each district and trained on various aspects of the study. Afterwards, the questionnaires were pre-tested on 24 randomly chosen households. The findings from the pre-test were used to fine-tune the survey instruments. The actual survey was finally administered through a face-to-face interview (to both solar users and non-users) between January and December of 2018**.** The data collected from the survey included household characteristics; lighting fuels; kerosene, electricity, candle, and dry-cell battery consumptions and expenditures, solar product types, supply sources, cost, power ratings, lighting hours per day and household - heads' assessment on benefits, qualities, and problems of solar products.

3.2.2. Direct field assessment

The household survey was accompanied by direct field assessment and characterization of each solar product identified during the household survey, jointly with the household-head and local solar technicians (field research assistants). The direct field assessment included identification of solar products by type, PV power generation capacity, product quality (with the help of solar technicians, and users), the current state of functionality, applications, number of LED bulbs, and capacity of batteries among others.

3.2.3. Key Informant Interviews

Key Informant interviews were carried out with a total of 15 purposively selected key informants consisting of local and district level solar technology promoters; solar PV importers, distributors, retailers and technicians; NGOs, and selected male and female solar user household-heads. The purpose was to understand the overall picture of solar technology dissemination, use, market trends, and challenges facing users. In addition, secondary data were gathered from Lighting Africa, Solarplaza, Solaraid, and several published and unpublished research works, and government and NGO reports.

3.3. Data analysis and presentation

3.3.1. Descriptive statistics and quantitative estimations:

Descriptive statistics and cross-tabulations were used to determine solar PV adoption rates and summarize explanatory variables. Analysis of Variance (ANOVA) was used to determine the significance of variations in mean kerosene consumptions between grid-electrified, solar-electrified, and non-electrified (neither grid nor solar) households. The average kerosene consumptions of non-electrified households were compared with the consumption of grid, and solar-electrified ones to estimate the kerosene consumption and energy expenditure savings of households from solar PVs and lanterns. Kerosene to BC and CO_2 emission conversion factors of 62.33 g/L (Lam et al. 2012a) and 2.45 kg/L (Chaurey and Kandpal, 2010) respectively were applied to estimate annual BC and CO_2 emission reductions of solar-users.

In addition, a score ranking method is used to assess the benefits of solar electrification as perceived by rural households. To that effect, the most important benefits of solar products were first established from key informant interviews and secondary sources. Afterwards, solar user households were asked to rank the benefits they obtain from the solar products from a scale of 1 to 5 where 5 is most important and 1 is least important.

3.3.2. Econometric analysis and model specification

To analyse the major factors influencing the adoption and purchase of solar PVs by rural households, an econometric analysis was carried out using a binary logistic regression (binary logit) model. Binary logit models are used to examine the relationship between a discrete dependent variable Y and one or more explanatory variables X (demographic, socio-economic, location, income, and access to credit service). Binary logit models use the maximum likelihood estimations to determine the likelihood of occurrence of an event from a dichotomous outcome of a dependent variable. The dependent variable 'Y' in this study represents the individual's or household's decision of purchase of solar PVs from a set of mutually exclusive choice categories (Y =1, purchase; Y= 0, otherwise), whereas the independent variables can take any form (discrete, continuous).

Let Y be the binary dependent variable (the probability that a rural household decides to adopt or purchase a solar product); the value of Y for household i (Y_i) has therefore only two outcomes: i.e. it takes $Y_i = 1$ if the household owns/purchases a solar lighting technology or $Y_i = 0$ otherwise.

Following Greene (2008) approach, the probability that household i decides to adopt solar product in the study areas can be mathematically specified as:

$$P_i = \Pr[Y_i = 1] = \frac{exp(\alpha + \beta X)}{1 + exp(\alpha + \beta X)} \qquad (2)$$

Where P_i is the probability that household i adopts solar products, and X_i is a vector of explanatory variables describing household i, α and β represents parameter estimates of the logit model.

Table 1. Definition of explanatory variables for the binomial Logit Model

Variable (X_i)	Definition of the variable
Gender of HH head	Dummy with D =1 for female and D = 0 for male
Age of HH head	Age of household-head in years
Education level	Education level of the HH head in number of years of schooling
Household size	Total number of household members
Children in school	Number of children in the family attending school
Gross annual income	Household gross annual income in ETB
Kerosene consumption	Household total annual kerosene consumption in litres
Distance to grid line	Distance between the household's home and the nearest power grid line in minutes
Distance to market	Walking distance between the household's home and the local market in minutes
Grid connection	Dummy with D =1 if the household is connected to the grid and D = 0 otherwise
Access to credit finance	Dummy with D =1 if the household has access to credit service and D = 0 otherwise
Location/district	Dummy: taking Mirab-abaya as a reference category, D1=1 if household lives in Aleta-wondo and D1 = 0 otherwise; D2 =1 if the household lives in Boloso-sore and D2 = 0 otherwise; D3 =1 if the household lives in Cheha and D3 = 0 otherwise

4. Results and Discussions

4.1. Characteristics of sample households

Of the total 660 sample households determined for the study, 605 completed the survey. The data collected from the remainder 55 were either incomplete or highly inaccurate when cross-validated and hence excluded. The overall response rate was thus 91.70%. Of the 605 who participated in the survey, 189 (31%) were from Aleta-wondo district, 204 (34%) from Boloso-sore, 134 (22%) from Cheha and 78 (13%) from Mirab-abaya districts. Table 2 presents descriptive statistics of the characteristics of the households surveyed. As shown in Table 2, out of the total 605 survey households, 84.13% were headed by males and the remaining 15.87% by females. The average educational status of household-heads, measured in terms of the number of years of schooling completed, was 4.73; and the average age of household-heads was 48.30 years. The average total household size was 6.24 persons but varies between 4.34 (in Cheha) and 7.0 (in Boloso-sore). The average landholding size was about 0.7 hectares (ha) per household with the highest holding (0.88 ha) in Boloso-sore and the lowest (0.53 ha) in Aleta-wondo.

Table 2. Descriptive statistics of characteristics of sample households

Variables		Statistic	Study areas (districts)				Total samples (N = 605)	SE
			Aleta-wondo	Boloso-sore	Cheha	Mirab-abaya		
Sample households		Num	189	204	134	78	605	
Gender of HH head	Male	Num	162	181	108	58	509	
	Female	Num	27	23	26	20	96	
Age of HH head		Mean	50.65	43.95	49.71	51.53	48.30	10.92
Education level of HH head		Mean	5.86	4.62	3.97	3.55	4.73	3.77
HH size (total)		Mean	6.76	7.00	4.34	6.29	6.24	2.38
Family members < 15 years		Mean	3.21	3.63	1.62	1.64	2.80	1.83
Total landholding in hectares, (ha)		Mean	0.53	0.88	0.65	0.74	0.70	0.64
Cattle heads size		Mean	3.06	3.44	2.85	5.83	3.50	2.36
Gross annual cash income in Ethiopian Birr (ETB)		Mean	28358	16579	17184	38123	22155	22350
Access to credit service		%	55.32	21.57	22.39	43.59	35.04	
Connected to the grid		%	40.74	8.82	29.85	75.64	32.06	
Walking distance to grid power line (minutes)		Mean	55.8	68.4	60.8	41.6	58.0	56.2

Source: Field survey, 2018.

The average cattle heads size per household is 3.50, with the highest holdings (5.83) in Mirab-abaya and lowest (2.85) in Cheha districts. The average gross annual cash income per household was estimated to be 22,155 Eth. Birr (ETB) roughly US$ 815 (in August 2018). However, household income varies markedly across the four study districts with the highest in the largely cash-crops growing districts of Mirab-abaya (ETB 38,123) and Aleta-wondo (ETB 28,358) compared with the mostly food-crops producing districts of Cheha (ETB 17,184) and Boloso-sore (ETB 16, 579) respectively.

With respect to access to credit financing, 55.3% and 43.6% of the respondents in Aleta-wondo and Mirab-abaya respectively reported having access to credit services (mainly from Omo Micro-Finance-Ethiopia) while only 22.4% and 21.6% of the respondents in Cheha and Boloso-sore districts respectively reported having access to credit service. About 32% of the sample households are connected to the national grid (Ethiopia's main electricity supplier). However, there is a stark gap in access to electricity among the four districts. So much that, more than 75% of the households in Mirab-abaya are connected to the grid while only 8.8% of the households in Boloso-sore are connected to the grid.

4.2. Uptake and characteristics of solar PV technologies in the study areas

4.2.1. Uptake of solar PV technologies

The adoption and use of stand-alone solar PV systems such as SHSs and PicoPVs in off-grid and rural areas of Ethiopia is steadily growing. As shown in Table 3, out of the 605 sample households, 137 (22.64%) own at least one solar PV system or lantern. Of which, most are primarily solar users for lighting and basic electricity ([1]solar-electrified) while some are using it for income generation activities, and a few are using the solar products as a backup to the grid power. This suggests that at least one in five rural households in the study areas has access to solar light. Of the 137 solar systems adopted by the sample households (typically one solar product per household), most (91.24%) were found in active use during the field assessment. Compared to the negligible use of solar products in rural Ethiopia back in 2010 (Lakew et al., 2017; GIZ, 2012), the market demand and use of solar products appear to have grown substantially over the last decade. In terms of geographic distribution, however, a considerable variation exists in the adoption of solar products between the four districts, partly due to variations in access to the grid.

Table 3. Household adoption of solar products in the study districts

Districts	Sample households	Grid-electrified	Solar-electrified	Non-electrified (neither grid nor solar)
Aleta-wondo	189	77 (40.74%)	37 (19.58%)	75 (39.68%)
Boloso-sore	204	18 (8.82%)	26 (12.75%)	160 (78.43%)
Cheha	134	40 (29.85%)	63 (47.01%)	31 (23.13%)
Mirab-abaya	78	59 (75.64%)	11 (14.10%)	8 (10.25%)
Total	605	194 (32.07%)	137 (22.64%)	274 (45.29%)

The highest rate of uptake of the solar technologies was observed in Cheha district with 47% of households solar-electrified; and the lowest in Boloso-sore district with 12.75% solar-electrified households. One possible explanation for this conspicuous variation is that Cheha district, located in close distance to the capital Addis Ababa (the main solar distribution centre), has better access to major solar suppliers with a relatively well-established market that facilitated the diffusion of the technology in the district.

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[1] Solar-electrified in this study refers to rural households that are primarily using SHSs and/or PicoPVs (LED lanterns) for domestic lighting, mobile phone charging, powering radios and/or running small businesses.

4.2.2. Characteristics of solar PV products in rural Ethiopia

A typical SHS in rural Ethiopia comprises one or more PV modules consisting of solar cells, a charge controller, and at least one battery to store the electricity produced by the solar panel. The SHSs operate at a rated voltage of 12 V direct current (DC) and provide power for low-voltage DC appliances for domestic lighting, mobile phone charging, and radios for 3 to 5 hours/day. In a few households, larger appliance SHSs with inverters (to change the 12V DC power to 240 V AC power) were found. In contrast, PicoPV is a small PV-system powered by a small PV panel with a battery that can be integrated into the lamp itself and provide a power output of 1Wp to 10Wp (GTZ, 2007).

The PicoPVs are mostly used for lighting and mobile phone charging. According to Solar Energy Foundation (Tsegaye, 2016), by 2016 there were a total of 1.1 million solar PVs and solar lighting systems distributed across Ethiopia. Of which, 100 000 were SHSs and the remaining 1 million were solar PicoPVs systems (mainly lanterns). Figure 3 presents the distribution of the solar products in the study areas by rated power of peak watt (Wp) based on our field assessments. About 63% of the solar user households own Pico-PVs (lanterns and simple systems) with PV capacity of up to 10 Wp; 30% own SHSs with PV capacity of 10Wp to 40 Wp; 5% own SHSs with PV capacity of 41 to 100 Wp; and close to 2 % own SHSs with power capacity above 100 Wp. The main reason for the preference of many solar users to PicoPV solutions as explained by the household heads surveyed and key informants is the high cost of larger capacity SHSs and conversely, the affordability, ease of portability, and simplicity of use of the PicoPV systems.

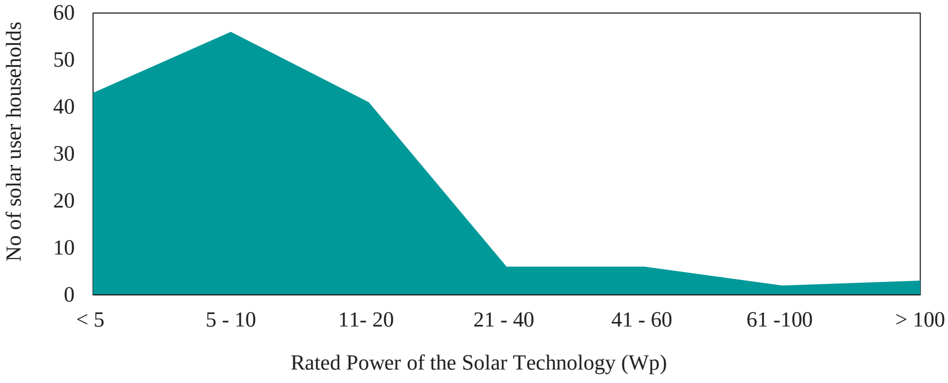

Figure 3. Distribution of solar products in the study area by power generation capacity

4.3. Impact of solar PV technologies

4.3.1. Impact on lighting energy access and kerosene consumption

Most (91.2%) of the solar users stated that access to convenient, safe, and high-quality lighting was the main reason they purchased the solar technologies. Respondents noted that solar PVs provided them with high-quality lighting on average for 3 to 5 hours a day and enabled them to minimize or avoid the use of kerosene for lighting. Consistent with the findings of Gustavsson and Ellegård, (2004) in Zambia, solar-electrified households pointed out that the quality lighting from the solar devices has improved their quality of life considerably. Beyond the access to quality lighting, the effect of solar use in reducing the kerosene consumption and dependence on low-efficiency kerosene wick-lamps was substantial. From our results (Table 4), the average monthly kerosene consumption of a non-electrified (neither grid nor solar) household is 4.46 litres, but this figure drops to 0.47 L when grid-electrified; and to 0.82 litres when solar-electrified. Based on these results, it was estimated that grid-electrified and solar-electrified households in the study areas could reduce their kerosene consumptions on average by 47.88 L (89.5%) and 43.68 L (81.60%) per year respectively compared to a non-electrified household.

Table 4. Household kerosene consumption by access to electrification

	Per month (L)	Per year (L)	Per capita (L)	Total kerosene savings (L/year)
Grid electrified	0.47	5.64	0.90	47.88 (89.5%)
Solar electrified	0.82	9.84	1.58	43.68 (81.6%)
Non-electrified	4.46	53.52	8.58	reference
Mean	2.36	30.01	4.53	
SE	2.76	24.16	3.87	

Source: Field survey, 2018.

Results from the ANOVA analysis in Table 5 showed that the variation in mean kerosene consumption between these three groups (grid-electrified, solar-electrified and non-electrified) is statistically significant, confirming that connection to the grid, and use of solar lighting do have significant effects on the households' kerosene consumption.

Table 5 Results of the ANOVA analysis of kerosene consumption between grid-electrified (194), solar-electrified (137) and non-electrified (274) household groups

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	326828.7	2	163414.4	283.875	3.9E-17	3.010
Within Groups	340212.7	591	575.656			
Total	667041.4	593				

Despite the significant reduction in kerosene consumption, 40% of grid-electrified and 30.5% of solar-electrified households stated using kerosene as a back-up and alternative fuel for lighting. In agreement with our findings, a comparative study of before and after electrification in rural Ethiopia by Barnes et al (2016), found that 25% of the households were using kerosene for lighting after being connected to the grid. Further analysis of the survey data showed that 19% of solar-electrified households use dry-cell batteries. And 7% of grid-electrified, and 5.5% of solar-electrified households use candles as back-up and secondary lighting fuels. In contrast, 34% of non-electrified households use dry-cell batteries to power hand-torches for lighting and radios.

It was estimated that a grid-electrified household, on average, consumes 4.25 pieces of (common size) taper candles and 0.5 dry-cell batteries per month; a solar-electrified consumes 2.0 candles and 1.7 dry-cell batteries per month. Likewise, a non-electrified household, on average, consumes 4.28 dry-cell batteries and 0.42 candles per month. These figures indicate that grid-electrified families rely more on candles to cope with frequent power outages; while solar-electrified households combine both candles and batteries to cope with the limited capacity of their solar PVs and poor performance of solar batteries. Conversely, most non-electrified households rely on dry-cell batteries to power hand torches and other dry-cell-battery-powered devices.

Table 6. Household candles and dry-cell batteries consumption by electrification

	Candles per month	Candles per year	Dry-cell batteries per month	Dry-cell batteries per year
Grid electrified	4.25	51.00	0.50	6.00
Solar electrified	2.06	24.52	1.70	20.28
Non-electrified	0.42	5.04	4.28	51.36
Mean	2.02	24.19	2.48	29.78
SE	1.77	21.21	1.84	28.03

Source: Field survey, 2018.

Reliability is a key factor in energy supply, as such the findings in Table 6 manifest that frequent power outages, and the unreliability of the grid power supply, and the limited capacity of the solar PVs (due to cost entailment) have compelled some rural households to continue to use kerosene wick lamps and candles despite their connection to the grid-electricity and use of solar power for lighting.

4.3.2. Impact on household fuel expenditures

The average price of kerosene per litre in the study areas in 2018 was ETB 23 per litre, the cost of one candle was ETB 5.00 and a pair of dry-cell battery ETB 24.00. Based on these market prices, a rural household in the study area spends, on average, ETB 54.58 per month for kerosene; ETB 9.98 per month for candles; ETB 29.78 per month for dry-cell batteries, and ETB 9.16 per month for grid-electricity (Table 7). These expenses sum up to a total average monthly expenditure of ETB 103.51 and annual expenditure of ETB 1242 per household. A closer examination of these expenses, however, sheds a light on the significant impact of solar lighting and grid connection on household fuel costs.

As shown by the results in Table 7, the total monthly expenditures of a rural household for lighting fuels decreases on average by ETB 89.71 (57.3%) when grid-electrified; and by ETB 107.55 (68.7%) when solar-electrified compared with non-electrified ones. By contrast, the average total monthly lighting fuel expenses of non-electrified households ETB 156.63 is more than three times the expenses of solar users and more than double of grid-electrified households.

Table 7. Monthly household lighting fuel expenditures by access to electricity in ETB

	Kerosene	Candles	Dry-cell battery	Grid electric	Total Lighting fuel expenses	Total fuel expenditure savings
Grid electrified	11.09	21.25	6.00	28.58	66.92	89.71 (57.3%)
Solar electrified	19.00	9.80	20.28	0.00	49.08	107.55 (68.7%)
Non-electrified	103.17	2.10	51.36	0.00	156.63	
Mean	54.58	9.98	29.78	9.16	103.51	
SE	81.71	7.65	19.08	35.43	148.34	

Extending the monthly energy expenditure savings above to annual savings suggests that a grid-electrified rural household could save up to ETB 1084.76 per year and solar-electrified could save ETB 1285.20 per year only from reduced energy costs as a result of the use of grid electricity and solar power respectively. The results imply that the use of solar PV significantly reduces household energy costs particularly from kerosene and dry-cell batteries. And therefore, households that have switched from kerosene lamps to solar products could gain substantial benefits from avoided fuel costs.

Under a simplified assumption that one million of the 1.1 million solar lighting devices disseminated in Ethiopia up until 2016 are functional or have been replaced by new solar products, the results in Table 7 imply that Ethiopia could avoid the import of 43.68 million litres of kerosene and save up to ETB 1.3 billion (US$ 48 million) per year. This equates to a reduction in Ethiopia's annual import of kerosene oil (295 million litres) and spending (US$ 177 million) by about 15%. For a largely poor country, this financial savings amounts to considerable assistance to the national and household economy and provision of critical public services. Given the high cost of conventional grid expansion in Ethiopia's rugged terrain, the results suggest that promoting solar electrification in rural and off-grid areas even with government subsidies is a viable option.

4.3.3. Impact on Black carbon (BC) and CO_2 emissions from kerosene wick lamps

Beyond providing quality lighting and economic benefits, replacing inefficient kerosene wick lamps with solar solutions presents significant climate benefits by reducing the emissions of BC and CO_2 (UNEP, 2013). Black carbon (BC) is a particulate matter formed from incomplete combustion of fossil fuels, wood, or other fuels (Lam et al., 2012a). It is a potent climate-warming agent second only to CO_2 due to its powerful absorption of sunlight (Jacobson et al., 2013). Moreover, BC is an extremely harmful particle to health with serious impacts on lung function and risks to tuberculosis and cancer (Lam et al., 2012b). According to IPCC (1996) estimates traditional kerosene lamps emit about 2.5 kg CO_2 per litre of kerosene. A study by Lam et al. (2012a) found that the combustion of kerosene in traditional simple wick lamps emits 62.33 g BC and 2.296 kg CO_2 per litre of kerosene. Similar estimates by Chaurey and Kandpal (2010) in India have shown that a single traditional kerosene lamp emits 2.45 kg CO_2/L of kerosene.

Based on these studies, we used a BC emission conversion factor of 62.33 g/L (Lam et al. 2012a) and CO_2 emission conversion factor of 2.45 kg/L of kerosene (Chaurey and Kandpal, 2010) to conservatively estimate the annual BC and CO_2 emission savings of grid-electrified and solar-electrified households as presented in Table 8.

Table 8. Annual black carbon (BC) and CO_2 emission savings from grid and solar lighting

	Annual kerosene savings (L)	Annual BC emission savings (kg)	Annual CO_2 emission savings (kg)
Grid electrified	47.88	2.98	117.31
Solar electrified	43.68	2.72	107.02
Mean	46.14	2.88	113.05
SE	4.14	0.25	10.14

The results showed that a grid-electrified rural household in the study areas on average saves the emission of 2.98 kg BC and 117.3 kg CO_2 per year from reductions in kerosene consumptions due to solar solution compared to non-electrified households. Likewise, a solar-electrified household on average saves emissions of 2.72 kg BC and 107 kg CO_2 per year compared to non-electrified households. These results show that, in addition to cost savings and quality lighting, solar PV systems and lanterns provide considerable benefits by reducing CO_2 emissions and the severe health and environmental impacts of BC from kerosene lamps. With an average life-cycle carbon footprint of 49.9 g CO_2e/kWh (Nugent and Sovacool, 2014), solar PVs systems could thus be an environmentally sound solutions to improve rural access to electricity in Ethiopia. Consistent with our results, a study in Bangladesh by Brossman (2013) reported that SHS user households were able to avoid the emissions of an average of 95.3 kg CO_2 per year.

Supposing that one million of the 1.1 million solar PVs and PicoPVs distributed across Ethiopia by 2016 are currently functional or have been replaced by new solar products, the country could save the emission of approx. 2,720 tons of BC and 107, 020 tons of CO_2 per year from solar lighting. For a country endeavouring to embrace a climate-resilient green economic development path, these savings represent a considerable gain for the national GHGs emissions abatement and climate change mitigation efforts.

4.3.4. Contribution to local development, income generation, and health

To further comprehend the benefits of solar PVs and PicoPVs, as perceived by the rural households, a score ranking method was used, following Coe (2007). Accordingly, solar users were asked to rank the benefits they derive from solar lighting systems from a list of already established benefits from a scale of 1 to 5 where 5 is the most important and 1 is the least. The major benefits of solar electrification were first established based on information from key informants, the preliminary surveys, and secondary sources. The calculated weighted mean score values of the rankings are shown in Figure 4.

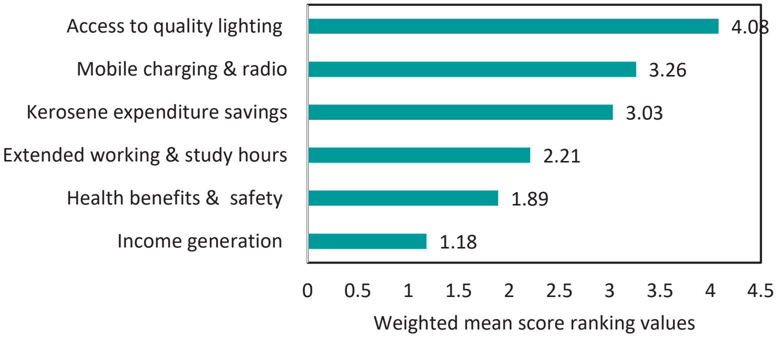

Figure 4. Weighted mean score-rankings of household benefits from solar PVs

According to the mean score rankings calculated, access to quality lighting is the primary benefit households obtain from solar products with a weighted mean score value of 4.08. The second most important benefit of solar PVs is the access to electricity for charging mobile phones and powering radios. Based on the data collected from solar users, it was estimated that the use of solar PVs has avoided the mobile charging expenses of a single household on average by ETB 40 - 60 per month (ETB 480 - 720 per year). Reductions in kerosene consumption and the resultant lighting fuel expenditure savings is ranked third, which reinforces our earlier finding that a solar-user household saves on average ETB 107.55 per month (ETB 1285 per year) from avoided energy costs compared with non-electrified households. These figures indicate that a SHS/PicoPV user household in rural southern Ethiopia could save a total of between ETB 1765 and 2005 (US$ 65 - 75) per year from reduced energy costs and avoided mobile charging costs.

For the mostly low-income rural families, this annual savings of US$65 - 75 from solar lighting amounts to non-negligible contribution to the household economy and welfare. From preliminary market assessments that we conducted in the study areas for quality-verified solar PVs, this annual cost saving of US$ 65 - 75 can recover the cost of a 10Wp SHS in less than 2.5 years. Furthermore, according to solar user households and micro-business owners, the benefits of solar PVs in improving the productivity, and extending the workdays and studying hours of family members were also significant.

Although less than 10% of the solar-users surveyed were engaged in income-generating activities that involved direct electricity use, the few that were engaged explained that the access to electricity from SHSs has considerably increased their income by extending working hours and creating new income generation portfolios such as mobile charging shops, rural barbershops, and kiosks. For example, two barbershop owner respondents in Cheha district who had installed a 150 Wp SHS stated that their income increased by approx. ETB 150 (US$ 5.5) per day after the installation of the solar PVs. Furthermore, it was found that some of the youth in the study areas were generating income of about ETB 150-300 per day from mobile charging and other small-businesses by using solar -electricity. These small- businesses were started after solar electrification and hence the access to solar PVs could be considered as the driving factor behind their establishment.

4.4. Constraints/problems facing solar PVs use in rural Ethiopia

To assess the major constraints and challenges facing the efficient use and widespread adoption of solar lighting systems, solar-user household-heads were asked to identify all the major problems and barriers they encountered through open-ended questions. The frequency of the responses is summarized and presented in Table 9.

Table 9. Constraints to the efficient and widespread use of solar PVs in rural Ethiopia

Problems/constraints	Frequency	Percentage (%)
Poor quality PV/lantern and short lifespan	65	47.44
Lack of after-sales maintenance and training	50	36.50
High cost of products from licensed distributors	48	35.04
Unreliable supply of quality-verified products	41	29.93
Lack of alternative financing and credit system	40	29.20
Lack of adequate know-how/operational skill	38	27.74

4.4.1. Poor quality products mainly from illegal/unverified supply sources

The primary challenge facing solar users in rural southern Ethiopia today is the flooding of the market with poor quality and counterfeit products. Many of the solar products currently in use in the study areas were purchased from illegal (black) markets that have no government approval, nor product guarantee. Consequently, many of the solar users (47.44%) reported experiencing failure in their solar PV systems, burning of lamps, battery failure, and reduced performance within a short period. As a result, they were compelled to purchase new solar products. In this line, a laboratory test was conducted by Lighting Global (2018) on 17 non-quality-verified Pico-PVs purchased directly from local markets in five developing countries including Ethiopia. The result showed that all the tested products failed to meet the Lighting Global quality standards due to one or more deficiency affecting product durability. In agreement with this finding, local solar technicians and key informants interviewed noted that many of the solar products in the market are counterfeit products from non-verified (black market) suppliers.

The quality problem, however, does not stop with the black-market dealers. According to the survey respondents and local solar technicians, even solar products from legal suppliers had quality and accountability problems. They underscored that there is little oversight of the quality and execution of guarantees of solar products even from legal suppliers. The Ethiopian government through the Ethiopian Standards Agency (ESA) in collaboration with Lighting Global has drafted a new Ethiopian standard for SHSs and PicoPVs (ES 6087/2017) in 2017 which was approved in 2018 to regulate the quality of imported solar products (ESA, 2019). According to this new standard, SHSs that are imported into the country must have at least a two-year warranty period for the main solar system including the PV modules; and one-year warranty period for the batteries and appliances; while all PicoPV systems should have a minimum of one-year warranty.

4.4.2. Lack of after-sales maintenance and technical support (training) service

There lies also a major challenge from the lack of after-sales maintenance and technical support services. This is due in large part to the fact that many of the solar products are acquired from black markets with no installation service or guarantee. Hence customers had to deal with installations by themselves or with the help of local technicians who themselves lack adequate skills. This led to faulty installations and technical problems that shortened the life of the solar system or part of the system. However, even when products are purchased from legal suppliers with a warranty, the chance that solar users will have after-sales maintenance and training services is minimal. Asked if solar users from legal suppliers have received after-sales maintenance and basic training, almost all replied otherwise but mentioned of receiving brief demonstrations from local agents and user guide leaflets. Respondents attested that despite having a two-year warranty certificate from the company that sold the product, problems such as early burnout of bulbs, failure of controllers, and fast draining of batteries were not solved.

4.4.3. High cost of quality approved products

Although the global price of solar PV modules has decreased sharply in recent years (IRENA, 2017), the high cost of SHSs from legal (licensed) suppliers remains one of the major barriers preventing rural households in the study areas from purchasing higher capacity SHSs. As a result, many had to buy low-quality SHSs from the black market at lower prices or buy lanterns that have limited capacity and use them only for lighting or mobile charging services. The price of a quality-verified 10Wp SHS including installation costs and accessories in the study areas in August 2018 was between ETB 4, 200 and 4, 500 (US$155-165) depending on the PV panel type (monocrystalline or polycrystalline) while the price of a non-quality verified 10Wp SHS from illegal suppliers (black market) was on average only ETB 2,450 (US$ 90).

4.4.4. Unreliable supply of solar products from legal importers and retailers

About 30% of solar users surveyed (most of them lanterns users) stated that even when they have the money to purchase higher capacity SHSs, the supply stock from licensed retailers is very limited and they often have to wait for 3 to 6 months until the products reach to local markets. According to local solar PV retailers interviewed, the problem of inadequate stock in part lies in the low purchasing power and working capital of the retailers. Along similar lines, a few solar importer company representatives interviewed stated that the lack of foreign currency in the country has forced them to wait up to a year before they have access to foreign exchange and import the solar products.

4.4.5. Lack of alternative and sufficient financing sources

Another hurdle expressed by solar users is the lack of credit financing and loan services to acquire quality-verified products. According to Girefie (2016), since 2012, Ethiopia's government through the Development Bank of Ethiopia (DBE) has launched an energy credit facility to Private Sector Enterprises (PSEs) and Micro Finance Institutions (MFIs) to help promote the use of renewable energy and energy-efficient technologies in rural/ off-grid areas of Ethiopia The DBE receives a forex credit line from the World Bank and provides a loan to PSEs and MFIs. With this credit line, households can get access to solar loans from local MFIs. A few solar users surveyed who had access to the DBE credit line explained that the solar loan is implemented in such a way that the household first saves a minimum of 5% of the cost of the solar product after which 95% of the cost is covered by the credit from the local MFIs. While these solar users acknowledge the importance of access to the credit, they maintain that the high-interest rate of 15 – 18% imposed by the MFIs has made the loan repayment too difficult. On the other hand, other solar users interviewed noted that access to the DBE credit line is very difficult since many MFIs are unwilling to provide the loan. Gorfu (2014) noted that the reluctance from MFIs was due to experiences of loan default and mismanagement from the debtors.

4.4.6. Lack of adequate knowledge and operational skill

Earlier market studies by GIZ (2012) suggested that the low level of awareness about solar PV systems among rural communities of Ethiopia was one of the biggest obstacles to the success of the solar market. Contrarily, findings from this study showed that most (> 75%) of the households surveyed have some level of awareness about solar PVs. Yet, significant (≈ 28%) number of solar users also stated that they lack the basic technical know-how and operational skills to properly use the products. This has contributed to some of the problems they faced in properly replacing fuses and bulbs, installation of solar PV systems or handling of solar batteries. Against this backdrop, the Solar Energy Foundation (SEF) has so far established some 14 solar - centres and trained technicians across Ethiopia (Schützeichel, 2012). While this initiative taken by SEF plays a key role model in improving the durability and reliability of solar products in the long term once installed, Solar Energy Foundation alone can only meet a fraction of the solar training service demand of the growing number of solar users across the country.

4.5. Determinants of solar PV adoption in rural Ethiopia

The empirical results from the binomial logit model indicate that several factors have a significant influence on the solar adoption decision of households in the study areas. As shown by the coefficient estimates in Table 10, the odds of adoption of solar products are positively and significantly associated with household income level, access to credit financing, number of children enrolled in schooling, and the location Cheha district.

Table 10. Binomial Logistic Regression Results: coefficients and odds ratios at 95% CI

Factor	Coef	SE Coef	Wald Test Chi-Square	P-value	Odds Ratio	95% CI
Gender of HH head	−0.411	0.379	1.17	0.279	0.663	(0.315, 1.394)
Age of HH head	−0.005	0.012	0.20	0.656	0.994	(0.970, 1.019)
Education of HH head	0.015	0.037	0.17	0.679	1.015	(0.943, 1.094)
HH size total	−0.155**	0.075	4.17	0.041	0.856	(0.738, 0.993)
Children in school	0.114**	0.095	5.42	0.023	1.120	(0.929, 1.352)
Gross annual income	0.180***	0.096	11.51	0.001	2.407	(1.911, 3.903)
Kerosene consumption	−0.082***	0.010	29.36	0.000	0.821	(0.702, 0.940)
Distance to Grid line	−0.095	0.075	1.57	0.211	0.909	(0.784, 1.055)
Distance to market	−0.090**	0.136	2.10	0.039	0.691	(0.360, 0.993)
Grid- connection	−2.936***	0.568	26.75	0.000	0.530	(0.217, 0.761)
Access to credit service	0.811**	0.288	7.93	0.019	2.249	(1.279, 3.954)
Location Aleta-wondo	−0.406	0.554	0.54	0.464	0.666	(0.224, 1.976)
Location Boloso-sore	−1.175**	0.379	5.72	0.017	0.308	(0.118, 0.808)
Location Cheha	0.687**	0.456	2.27	0.013	1.988	(0.812, 3.862)
Constant	1.772	0.945				
Observations	605					

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

Mirab-abaya is the reference category set for the dummy variable Location

Goodness-of-Fit Tests

Test	DF	Chi-Square	P-Value
Deviance	588	424.77	1.000
Pearson	588	800.35	0.000
Hosmer-Lemeshow	8	15.42	0.042

Model Summary

Deviance R-Sq	Deviance R-Sq(adj)	AIC
38.69%	36.38%	458.77

The results suggest that households with higher income levels are more likely to invest in solar PVs than the poorer ones. Consistent with our results, other studies (Guta, 2018; Lay et al., 2012; Komatsu et al., 2011) in Ethiopia, Kenya, and Bangladesh have reported that an increase in household income is positively and significantly associated with an increase in the likelihood of solar adoption. Likewise, the probability of adoption of solar technologies increases with an increase in access to a credit facility. This is because the purchase of solar products, particularly SHSs, requires considerable spending. As such, increased access to credit reduces the burden from high upfront cost and increases the likelihood of adoption of SHSs by rural households.

The significant and positive coefficient for the location Cheha compared to Mirab-abaya is likely due to the presence of well-established solar markets, increased awareness, and spill-over effects from early adopters in the area. The positive and significant coefficient for the number of children enrolled in schooling supports the prior discussion where solar users noted that access to solar lighting enabled their children to study for longer hours in the evening. Although statistically weak, the educational level of the household-head is positively associated with the adoption of solar products. This may indicate that an increase in the education level of the household-head, awareness and preference for clean lighting energy increases.

However, the insignificant influence of the education level may also suggest that factors such as household income and access to credit rather play a larger role than education in the solar adoption decision as many of the households have some level of awareness. The likelihood of solar adoption is negatively and significantly related to household size, kerosene consumption, distance to market, grid connection, and the location ‘Boloso-sore’ district. As was mentioned by Giri and Goswami (2017) in Nepal, access to grid electricity makes the adoption of solar PVs significantly unlikely. The reason is that households who are already connected to the grid are paying electricity utility bills and thus are less likely to purchase solar products which would require additional spending. Beyond the cost factor, Karakaya and Sriwannawita (2015) noted that grid-connected households may perceive solar products as having low level of utilization with limited durability and efficiency, and hence not worthy of investment.

The possible explanation for the negative and significant association between kerosene consumption and solar adoption could be that higher quantity kerosene consumption is related to low-income households residing in relatively remote areas and therefore are less likely to purchase solar PV systems. The barrier from low-income levels (high cost of solar products) and limited access to credit finance is more evident in Boloso-sore district where the adoption of solar PVs is negatively and significantly linked with the district, compared to Mirab-abaya.

The distance to market (town) of the household's home is negatively and significantly associated with the adoption of solar PVs. This implies that households residing closer to the market (town) and road networks are more likely to adopt solar technology than those that are distant. This is because of the accessibility of solar products. In a country with undeveloped rural road network, the diffusion of solar products is heavily reliant on accessibility and transportation infrastructures. Asa result, households that dwell closer to the highway roads and market centres are more likely to have access to solar products than those in remote areas. Despite Rahut et al. (2017) suggesting that solar is a remote household phenomenon, accessibility and transportation play a key role in the diffusion of solar technologies in Ethiopia.

Contrary to the findings of earlier studies (Mutua and Kimuyu, 2015; Giri and Goswami, 2017), the reason for the negative and significant relation between solar adoption and household size could be that larger families need more rooms and hence more lighting, which means higher capacity SHSs that are expensive. Therefore, households with large family sizes may rather wait for grid expansion to arrive. Though statistically weak, the gender (female) and age of the household-head are both negatively related to adoption of solar technology, indicating that households with male and younger heads are more likely to adopt solar technologies than those with female and older heads. This is due to the reason that households headed by males tend to have better income and purchasing power for various reasons related to gender-inequalities and cultural factors. Likewise, younger households tend to have better education and awareness on solar technology and hence improves the odds of adoption of solar technology.

5. Conclusions and recommendations

5.1. Conclusions

The main aim of this study was to assess and empirically analyse the impacts of stand-alone solar PV systems on rural household energy access, socio-economic development, and the environment in southern Ethiopia. The findings showed that the uptake of solar PV systems and lanterns is growing fairly quickly. The most important benefit of solar lighting technologies was the access to clean and quality lighting, and basic electricity; and the resultant reduction in household kerosene use for lighting. The study finds that the kerosene consumption of solar-electrified rural families decreased on average by 43.68 L (81.6%) per household per year compared to non-electrified ones. The access to solar lighting and basic electricity from solar home systems and lanterns could enable a solar-electrified rural household to save ETB 1765 - 2005 (US$65 - $75) per year only from reduced energy costs and avoided mobile charging fees. Given the high capital cost of grid expansion to most rural areas in Ethiopia, the findings present strong evidence to promote the large-scale adoption, dissemination, and utilization of solar PVs products even with subsidies and soft loans from the (Ethiopian) government.

Beyond the access to quality lighting and reduced energy costs, the findings also showed that a solar-electrified rural household could save the emissions of on average 2.72 kg of Black Carbon and 107.02 kg of CO_2 per year compared to a non-electrified household. This suggests that solar PV systems are not only viable solutions for rural electrification but could also contribute to climate change mitigation efforts. According to the survey households, access to solar lighting has reduced their exposure to indoor pollution and health risks associated with traditional kerosene wick lamps. The study also finds that SHSs have created new income-generating activities as well as increased incomes of existing micro-enterprises. The empirical results from the binary logit model showed that household's income level, location, and access to credit finance are among the major factors positively and significantly influencing solar adoption while access to grid and distance to market were found to be negatively associated with solar use.

Overall, the evidence from the present study reveals that the use of stand-alone solar PV systems for rural electrification in rural Ethiopia is providing households with access to basic electricity, improved quality of life, health and socio-economic conditions while reducing their energy costs, kerosene consumptions, GHGs emissions and the associated negative environmental and health effects from traditional wick lamps. This provides a strong basis to further promote and integrate solar PV systems in the national energy sector development strategies of Ethiopia and many other under-electrified developing countries. Yet, the sustainability, efficacy, and widespread use of solar PVs systems is facing some serious challenges. The primary challenge is the poor quality of products in the market mainly from illegal (black market) suppliers at low prices. Another related obstacle is the lack of after-sales maintenance service and technical support from solar PV suppliers which in turn is linked to the purchase of most of the solar products from the black market without any warranty. The flooding of the market with low-quality and sub-standard solar products is also attributable to the limited supply of quality-verified products from legally accredited distributors and the high price of quality-verified solar products vis-a-vis the disposable income of the rural poor. In light of these problems and barriers, the study suggests the following recommendations.

5.2. Recommendations

- Build the technical capacity of solar users and local technicians through the provision of basic training and establishing more solar centres within the rural setting
- Encourage local production, assembly, and manufacturing of solar products and spare parts
- Enforce the national solar regulation and the Global Lighting quality standards
- Enforce product warranty certificates and after-sales services with legal assistance to users
- Increase consumer awareness and education on product quality standards and testing
- Make quality-verified products affordable through VAT tax waiver, subsidies, and soft loans
- Encourage local micro-finance institutions to provide solar loans to potential users
- Encourage solar retailers to adopt alternative payment models such as PAY-AS-YOU-GO
- Avail foreign exchange and loans to licensed and quality solar importers and distributors
- Streamline and re-engineer the solar import regulations, taxation, and licensing process
- Empower local solar retailers by providing start-up capital and skill training
- Provide entrepreneurial skill training for solar users for more productive and diversified income-generating use of the technologies for stronger economic impact
- Increase awareness-raising at the community level to sustain the market for solar products

6. References

Admasu, A.A. (2011). Solar PV Based Rural Electrification in Rema Rural Village in Ethiopia. MSc Thesis. Royal Institute of Technology in Stockholm KTH. https://www.diva-portal.org/smash/get/diva2:420710/FULLTEXT01.pdf (Accessed 03.03.19).

Barnes, D.F., Golumbeanu, R., Diaw, I. (2016). Beyond Electricity Access: Output-Based Aid and Rural Electrification in Ethiopia. Energy for Development, The World Bank, Washington DC. http://documents.worldbank.org/curated/en/781791487789244953/pdf/112967-WP-P105651-PUBLIC-Beyond-Electricity-Access-Ethiopia-FINAL.pdf (Accessed 11.01.19).

Bekele, B., Palm, B. (2010). Feasibility study for a standalone solar-wind-based hybrid energy system for application in Ethiopia. Applied Energy, 87(2):487-495.

Bekele, G., Boneya, G. (2012). Design of a Photovoltaic-Wind Hybrid Power Generation System for Ethiopian Remote Area. Energy Procedia, 14:1760 – 1765.

Bekele, G., Tadesse, G. (2012). Feasibility study of small Hydro / PV / Wind hybrid system for off - grid rural electrification in Ethiopia. Applied Energy, 97(C): 5-15.

Brossmann, M. (2013). Off-grid Rural Electrification and Fighting Poverty. A Comparative Impact Assessment of Solar Home Systems and Small Solar Home Systems in Rural Bangladesh. Global Studies Working Papers No 19, University of Tübingen. https://publikationen.uni-tuebingen.de/xmlui/handle/10900/50005 (Accessed on 14.06.19).

Buragohain, T. (2012). Impact of Solar Energy in Rural Development in India. Int Journal of Environmental Science and Development, 3(4): 334-338.

Chaurey, A., Kandpal, T.C. (2010). Assessment and evaluation of PV based decentralized rural electrification: An overview. Renew. Sustain. Ene Rev., 14: 2266– 2278.

Cochran, W.G. (1977). Sampling Techniques, Wiley, New York.

Coe, R. (2007). Analysing data from participatory on-farm trials. African Statistics Journal, 4 (89-121).

CSA. (2013). Central Statistical Agency of Ethiopia. Population Projection for All Regions from 2014 – 2017. Addis Ababa. https://www.academia.edu/30252151/Federal_Democratic_Republic_of_Ethiopia_Central_Statistical_Agency_Population_Projection_of_Ethiopia_for_All_Regions_At_Wereda_Level_from_2014_2017(Accessed 03.03.19).

Ecofys. (2016). Off-grid Rural electrification in Ethiopia: NAMA developed within the Mitigation Momentum project, Ministry of Water and Energy (MoWIE). http://www.mitigationmomentum.org/downloads/NAMA-proposal-for-Off-grid-Rural-electrification-in-Ethiopia_April-2016.pdf (Accessed 19.03.19).

EEP. (2014). Power Sector Development: Electricity Demand Forecast. Ethiopian Electric Power EEP. https://pubs.naruc.org/pub.cfm?id=537C14D4-2354-D714-511E-CB19B0D7EBD9 (Accessed 24.05.19).

ESA. (2017). Ethiopian Standard Agency Requirements for DC Solar Home System Kit. Ethiopian Standard: ES 6087. https://www.undp.org/content/dam/ethiopia/docs/Ethiopia%20Final%20-%20ES%206087-2017%20Requirements%20for%20DC%20Solar%20Home%20System%20Kit.pdf (Accessed 01.07.19).

Feron, S. (2016). Sustainability of Off-Grid Photovoltaic Systems for Rural Electrification in Developing Countries: A Review. Sustainability, 8:1326.

Giday, Z.G. (2014). Technical and Economic Assessment of solar PV/diesel Hybrid Power System for Rural School Electrification in Ethiopia. Int Journal of Renewable Energy Research, 3(3).

Girefie, Y. (2016). Market Development for Renewable Energy and Energy Efficient Products Credit Line Status Report. Ethiopian Development Bank 2016. https://www.gogla.org/sites/default/files/documenten/session_6c_-_panel_-_working_capital_needs_including_development_bank_of_ethiopia_slides.pdf (Accessed on 31.07.19).

Giri, M., Goswami, B. (2017). Determinants of households' choice of energy for lighting in Nepal. Economics and Business Letters, Oviedo University Press, 6(2): 42-47.

GIZ. (2012). Solar PV System Baseline Market Assessment in Ethiopia. German Development Agency, GIZ. https://energypedia.info/wiki/PicoPV_System_Market_Assessment_in_Ethiopia (Accessed 19.04.19).

Gorfu, Y. (2014). Dissemination of Solar Energy Technologies in Ethiopia: Successes, Challenges and Opportunities. Paper published in the proceedings of a National Workshop. Addis Ababa, May 19–20, 2014. http://www.hoarec.org/docs/ESEF%20Proceedings_HD.pdf (Accessed on 30.07.19).

Greene, W.H. (2008). Econometric Analysis. 6th Edi., Pearson Prentice Hall.

GTZ. (2007). Eastern Africa Resource Base: GTZ Online Regional Energy Resource Base: Regional and Country Specific Energy Resource Database, GTZ. https://energypedia.info/wiki/East_Africa:_Overview_of_Regional_Energy_Resources (Accessed on 14.02.19).

Gustavsson, M., Ellegård, A. (2004). The impact of solar home systems on rural livelihoods. Experiences from the Nyimba Energy Service Company in Zambia. Renewable Energy, 29(7): 1059-1072.

Guta, D.D. (2018). Determinants of household adoption of solar energy technology in rural Ethiopia. Journal of Cleaner Production, 204:193-204.

Harsdorff, M., Bamanyaki, P. (2009). Impact Assessment of the Solar Electrification of Micro Enterprises, Households and the Development of The Rural Solar Market in Uganda, GTZ. https://energypedia.info/images/d/d4/Impact_assessment_shs_preeep_uganda_2009.pdf (Accessed 15.02.19).

Hassan, F., Lucchino, P. (2016). Powering Education: CEP Discussion Papers No 1438, Centre for Economic Performance, LSE. http://app. olela.net/infomap/files/classOffGrid/OGL_IND.pdf (Accessed 22. 05. 19).

IEA. (2012). Pico Solar PV systems for Remote Homes. Photovoltaic Solar Systems programme. International Energy Agency. http://www.iea-pvps.org/fileadmin/dam/public/report/technical/rep9_12_PVPS_Pico_Solar_PV_Systems_apr13.pdf (Accessed 01.01.19).

IPCC. (1996). Guidelines for national greenhouse gas inventories, Reference Manual (Volume 3), revised 1996; Intergovernmental Panel for Climate Change.

IRENA. (2018). Renewable Power Generation Costs in 2017. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf (Accessed 01.06.19).

Jacobson, A., Lam, N.L., Bond, T.C., Hultman, N. (2013). Black Carbon and Kerosene Lighting: An Opportunity for Rapid Action on Climate Change and Clean Energy for Development. The Brookings Institution 1775 Washington, DC. https://www.humphreyfellowship.org/system/files/Climate%20Change%20and%20Development%20-%20Brookings.pdf (Accessed 13.05.19).

Karakaya, E., Sriwannawita, P. (2015). Barriers to the adoption of photovoltaic systems: The state of the art. Renewable and Sustainable Energy Revi., 49: 60–66.

Keane, J. (2014). Pico-Solar Electric Systems: The Earthscan Expert Guide to the Technology and Emerging Market, Earthscan Routledge.

Kebede, K.Y., Mitsufuji, T. (2017). Technological innovation system building for diffusion of renewable energy technology: A case of solar PV systems in Ethiopia. Technological Forecasting & Social Change, 114: 242-253.

Kebede, K.Y. (2015). Viability study of grid-connected solar PV system in Ethiopia. Sustainable Energy Technologies and Assessments, 10: 63-70.

Komatsu, S., Kaneko, S., Shrestha, R. M., Ghosh, P.P. (2011). Non-income factors behind the purchase decisions of solar home systems in rural Bangladesh. Energy for Sustainable Development, 15: 284–292.

Kudo, Y., Shonchoy, A., Takahashi, K. (2015). Impacts of Solar Lanterns in Geographically Challenged Locations: Experimental Evidence from Bangladesh. IDE Discussion Papers No. 502.

Lakew, H., Hailu, B., Hailu, T., Carter, S. (2017). A climate for solar power: Solutions for Ethiopia's energy poverty. Policy Brief. Climate and Development Knowledge Network (CDKN).

Lakew, H., Tesfaye, G., Yirgu, A. (2011). Low-carbon Africa: Ethiopia. Christian aid Ethiopia. https://www.christianaid.ie/sites/default/files/2017-08/low-carbon-africa-ethiopia-november-2011.pdf (Accessed 11.06.19).

Lam, N. L., ..., Bond, T.C. (2012a). Household Light Makes Global Heat: High Black Carbon Emissions from Kerosene wick Lamps. Environmental Science & Technology, 46(24): 13531- 13538.

Lam, N.L., Smith, K.R., Gauthier, A., Bates, M.N. (2012b). Kerosene: A Review of Household Uses and their Hazards in Low- and Middle-Income Countries. J. Toxicol. Environ. Health Part B, 15 (6): 396–432.

Lay, J., Ondraczek, J., Stöver, J. (2012). Renewables in the energy transition: Evidence on solar home systems and lighting fuel choice in Kenya. HWWI Research Papers No 121, Hamburg Institute of International Economics.

Lemma, M. (2014). Power Africa Geothermal Roadshow: Ethiopian Electric Power Strategy and Investment Division, The Ethiopian Electric Power (EEP). https://geothermal.org/Annual_Meeting/PDFs/Mekuria%20Lemma%20Geothermal.pdf (Accessed 05.01.19).

Lighting Africa (2012). Policy Report Note Ethiopia. https://www.lightingafrica.org/wp-content/uploads/2016/07/26_Ethiopia-FINAL-August-2012_LM.pdf ((Accessed 05.01.19).

Lighting Africa/Ethiopia. (2019). Reaching out to Rural End-Users. https://www.lightingafrica.org/country/ethiopia/ (Accessed 11.06.19).

Lighting Global/Africa. (2018). Quality Matters. Lighting Global Network. https://www.lightingglobal.org/news/quality-matters/ (Accessed 9.5.19).

Mondal, A.H., Klein, D. (2011). Impacts of solar home systems on social development in rural Bangladesh. Energy for Sustainable Development, 15 (1): 17-20.

Müggenburg, H., ..., Peter, A. (2012). Social acceptance of PicoPV systems as a means of rural electrification — A socio-technical case study in Ethiopia. Energy for Sustainable Development, 16 (1): 90-97.

Mutua, J., Kimuyu, P. (2015). Exploring the Odds for Actual and Desired Adoption of Solar Energy in Kenya. Environment for Development. Discussion Paper Series No EfD DP 15-14.

Nugent, D., Sovacool, B. (2014). Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy, 65: 229-244.

Obeng, G.Y., Evers, H.D. (2010). Impacts of public solar PV electrification on rural micro-enterprises: The case of Ghana. Energy Sustain. Dev., 14:223–231.

Rahut, D.B., Mottaleb, K.A., Ali, A., Aryal, J. (2017). The use and determinants of solar energy by Sub-Saharan African households. International Journal of Sustainable Energy, 37(8): 718-735.

Rebane, K.L., Barham, B.L. (2011). Knowledge and adoption of solar home systems in rural Nicaragua. Energy Policy, 39: 3064–3075.

Schützeichel, H. (2012). Ethiopia solar. Solar Energy Foundation. https://sun-connect-ea.org/solar-villages-a-successful-model-for-promoting-local-solar-companies/ (Accessed 11.05.19).

SolarAid. (2014). Solar Impact Report in Kenya, Tanzania, Zambia, Malawi and Senegal. https://solar-aid.org/wp-content/uploads/2016/09/SolarAid-Impact-Report-2014.pdf (Accessed 23.03.19).

SolarPlaza. (2017). Ethiopia Solar Report: The Solar Future: Deserts of Africa. https://africa.thesolarfuture.com (Accessed 25.06.19).

Tedsen, E. (2013). Black Carbon Emissions from Kerosene Lamps: Potential for a new CCAC Initiative, Ecologic Institute, BerliN 2013. https://www.ccacoalition.org/sites/default/files/resources/black-carbon-and-kerosene-lamps-study.pdf (Accessed 23.04.19).

Tsegaye, S. (2016). Solar Energy Foundation: Experiences and Best Practices in Ethiopia. https://sustainabledevelopment.un.org/content/documents/22747Solar%20Energy%20Foundation%20experiance%20and%20best%20practices.pdf (Accessed 23.06.19).

UNEP. (2013). Sustainable Off-Grid Lighting Solutions Can Deliver Major Development and Climate Benefits. UNEP. https://www.unenvironment.org/news-and-stories/press-release/sustainable-grid-lighting-solutions-can-deliver-major-development (Accessed 15.03.19).

Urmee, T., Harries, D. (2011). Determinants of the success and sustainability of Bangladesh's SHS program. Renewable Energy, 36 (11):2822-2830.

Wamukonya, N., Davis, M. (2001). Socio-economic impacts of rural electrification in Namibia: comparisons between grid, solar and unelectrified households. Energy for Sustainable Development, 5(3):5-13.

Wang, L., Bandyopadhyay, S., Cosgrove-Davies, M., Samad, H. (2011). Quantifying Carbon and Distributional Benefits of Solar Home System Programs in Bangladesh. Policy Research Working Paper No 5545. The World Bank.

Wijayatunga, P.D.C., Attalage, R. (2005). Socio-economic impact of solar home systems in rural Sri Lanka: a case-study. Energy for Sustain. Develop., 9(2):5-9.

World Bank. (2019a). The World Bank in Ethiopia: Overview. https://www.worldbank.org/en/country/ethiopia/overview (Accessed 3.4.19).

World Bank. (2019b). Access to electricity, rural (% of rural population) Ethiopia. https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=ET (Accessed 01.03.19).

World Bank. (2010). Solar lighting for the base of the pyramid: overview of an emerging market (English). Washington, D.C. http://documents.worldbank.org/curated/en/455781501150966250/Solar-lighting-for-the-base-of-the-pyramid-overview-of-an-emerging-market (Accessed 23. 06.19).

Paper V

Household energy consumption patterns and the share of renewable and modern energy sources in rural southern Ethiopia

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Abstract

Over 90% of Ethiopia's total final energy is consumed by households and about 80% of the population lives in rural areas. Using cross-sectional data from a survey of 605 rural households and direct energy consumption measurements, this paper analyses current rural household energy consumption patterns and the share of renewable and modern sources in southern Ethiopia. The results showed that more than 97% of the households sampled depend on traditional solid biomass fuels, mainly fuelwood, as primary energy sources for cooking and baking end-uses. In contrast, about 50% use kerosene, 29% grid electricity, 19% solar lighting, and 1.98% biogas as primary energy sources for lighting. Analysis of household energy consumption by source showed that traditional biomass fuels dominate the household energy mix accounting for 85 278 MJ (97.8%) of the total 87 172 MJ energy consumed by a household per year. By contrast, energy from modern and clean sources (electricity, biogas, and solar) combined accounted for 830 MJ (0.95%) while kerosene constituted 1064 MJ (1.22%). The study finds that access to modern and renewable energy sources and technologies has led to significant energy substitution from kerosene-based to modern and clean lighting. However, we found no evidence of substantive energy substitution or decline in solid biomass dependence for cooking and baking end-uses which make up the bulk (over 97%) of the household energy demand. This signifies that while strengthening the current endeavours of rural electrification, Ethiopia needs to develop alternative and more sustainable biomass energy sources, and energy-efficient and affordable cooking and baking technologies.

Keywords: *Rural households, energy sources, consumption patterns, traditional biomass fuels, clean fuels, energy substitution, energy transition*

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1. Introduction

With an estimated population of 109 million people (as of 2018), Ethiopia extends over an area of 1.1 million km^2 in the horn of Africa (World Bank, 2018a). It is estimated that the country is endowed with vast renewable energy resources with power generation potential of 45 gigawatts (GW) from hydropower; 100 GW from wind power; 7 GW from geothermal and abundant solar power with an average irradiance of 5.5 kWh/m^2/day (Mondal et al. 2018; Lemma, 2014). If this potential is effectively harnessed, Ethiopia could not only achieve energy security to drive its social and economic development but could also generate substantial revenue from power exports to regional markets (Khan and Singh, 2017). Given its rapid economic expansion and population growth in recent years; ensuring access to modern, affordable and sustainable energy services is crucial for Ethiopia to meet its growing energy demand and mitigate the adverse environmental and health impacts of unsustainable use of traditional solid biomass fuels.

Yet, Ethiopia's vast energy production potential remains largely untapped and chronic energy shortages and low rates of access to modern energy services continue to stifle its development strides. Despite the considerable gains made in hydro-power generation in recent years, the national energy balance remains dominated by solid biomass fuels. According to recent data from IEA (2018), biomass and bio-wastes accounted for 47.05 (91.4%) out of the 51.54 MTOE (million ton of oil equivalent) of total primary energy supply in Ethiopia in 2016 while electricity constituted only 0.895 mtoe (1.74%). In the final energy consumption, biomass accounted for 37.87 (90%) out of the 42.15 mtoe of the total final energy consumed in 2016 (IEA, 2018).

A closer look at the share of the different sectors in the final energy consumption shows that the household sector is by far the largest energy consumer accounting for more than 90% of the total energy consumed in the country followed by the transport 4%, and manufacturing/industry 3% (IEA, 2018). Within the household sector, about 98% of the total final energy consumed in Ethiopia for the period 2014 to 2015 was derived from primary and delivered biomass energy (Yurnaidi and Kim, 2018).

According to some studies, over 90% of the household energy consumption in Ethiopia is used for cooking and '[1]Injera'-baking (Mulugeta et al., 2017; Kebede and Kiflu, 2014). In rural areas where 80% of Ethiopia's population lives (World Bank, 2018a), modern energy services are inaccessible, hence traditional biomass and fossil fuels dominate the household energy supply (Guta, 2014; CSA, 2012; Gebreegziabher, 2007).

As a result, Ethiopia faces multiple challenges in its quest for ensuring energy security and climate-resilient and sustainable development. On the one hand, unsustainable exploitation and heavy dependence on biomass fuels is depleting the country's forest resources with adverse environmental consequences (Guta, 2014; Asfaw and Demissie, 2012). According to FAO (2015) estimates, Ethiopia lost on average 105,000 hectares (ha) or 0.8% of its forests per year between 1990 and 2015, a substantial amount of which is directly linked to fuelwood collection and charcoal production for domestic energy supply (Duguma et al., 2019; Guta 2011). The projections made by the Ethiopian Forestry Action Program (EFAP, 1994), also show that Ethiopia's demand for fuelwood for 2014 (88.9 million m^3) was ten times as much as the sustainable supply (8.8 million m^3). This has a direct bearing on the country's forests and climate change mitigation potential. On the other hand, limited access and unreliable supply of modern energy such as electricity is undermining Ethiopia's effort to achieving rapid, and sustained economic growth (Abdisa, 2018; Carlsson et al., 2018; Mondal et al., 2018).

Cognizant of the pressing need to fundamentally reshape the country's development path vis-à-vis the energy sector, Ethiopia initiated an ambitious Climate Resilient Green Economy Strategy (CRGE) in 2011 that integrates rapid economic growth with large greenhouse gases (GHGs) emission reduction thereby transitioning the country to a middle-income status by 2025 (FDRE, 2010). In pursuit of this goal, Ethiopia crafted a series of Growth and Transformation Plans (GTP) with high priorities placed on the development of its renewable energy potential and expansion of energy infrastructures. The goal is to ensure access to modern, affordable, clean, and sustainable energy for all.

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[1] *'Injera'*- is a thin round flatbread consumed in much of Ethiopia that uses up more than 50% of the total household energy demand (Mulugeta et al., 2017; Kebede and Kiflu, 2014)

Guided by the CRGE, the energy sector during the first GTP period (2011 to 2015) had aimed at expanding the total installed power generation capacity of the country from 2 GW in 2010 to 10 GW by 2015, and thereby to increase the national electricity coverage from 41% in 2010 to 75% in 2015, and 90% by 2020 (FDRE, 2010; 2016). Although the implementation of the GTP I fell short of its targets, the country made modest progress in hydropower generation. The second Growth and Transformation Plan (GTP II) was launched in 2016 with an implementation period of 2016 to 2020 (FDRE, 2016). Capitalizing on the modest achievements of the GTP I, the energy sector for GTP II set forth an overall goal of increasing the country's power generation capacity from 4.18 GW in 2015 to 17.208 GW by 2020 (FDRE, 2016).

Foremost among the strategies pursued by the Ethiopian government for improving rural access to modern energy and increased energy efficiency are rural electrification through grid expansion; off-grid electrification through stand-alone solar Photovoltaic (PVs) systems; and dissemination of biogas and improved cookstoves (ICS). To that end, the Ministry of Water, Irrigation, and Electricity (MoWIE) had planned the deployment of 400,000 Solar Home Systems (SHS) and 3.6 million Solar PicoPV systems (lanterns), 3,600 institutional PVs and 3,600 solar cookers by 2020 (FDRE, 2016). The National Biogas Programme had planned the construction of 14,000 biodigesters during its first implementation phase (2008-2013) and 20, 000 in its second implementation phase (2014 - 2017) (Wassie and Adaramola, 2019). The National Programme for Improved Biomass Cook Stoves had planned for the dissemination of 9.415 million ICS in GTP I and 11.45 million more in GTP II (FDRE, 2010: 2016).

In view of these efforts, reports from the government of Ethiopia and its development partners (FDRE, 2016, Power Africa, 2018; Barnes et al., 2016) suggests that rural access to modern energy is increasing and national electricity coverage has risen from 41% in 2010 to 60% in 2015 with rural electricity access spurring to 31% from just 6.6% in 2010. According to these reports (FDRE, 2016), by the end of GTP I, more than 2 million solar technologies, and 15 million ICSs had been distributed and 12, 071 biogas plants had been constructed (MEFCC, 2017; SNV, 2019). Per-capita electricity consumption has increased from 23 kWh per year in 2000 (World Bank, 2015; SE4ALL, 2017) to 41 kWh by 2008, and 100 kWh by 2016 (IEA, 2019). A few published studies also indicate that the social acceptance of solar PVs/lanterns is growing (Müggenburg et al., 2012).

Aside from these reports and a few qualitative studies, in-depth studies and up-to-date empirical evidence on the current picture of rural household energy use patterns, and the effects of access to renewable and modern sources on the rural households' energy mix and biomass dependence is barely available. Although rural households make up the largest energy consumer groups in Ethiopia, most of the studies so far have focused on urban consumers (e.g. Guta et al., 2015; Gebreegziabher et al., 2012; Mekonnen and Köhlin, 2009; Kebede et al., 2002). The few studies conducted on rural household energy use were either nonrecent (e.g. Mekonnen, 1999; Mulugetta, 1999; Gebreegziabher, 2007;) or were mostly limited to a part of the household energy mix (e.g. Yurnaidi and Kim, 2018; Tucho and Nonhebel, 2015; Guta, 2014). As a result, substantial knowledge gaps remain concerning the interaction and effect of access to modern and renewable energy sources such as electricity and solar on rural household energy use patterns and the energy transition process in Ethiopia. Neither is the share of energy from renewable and modern sources in the household energy mix quantified especially in rural areas. Establishing up-to-date empirical evidence and comprehensive understanding of the rural household energy use patterns and transition process is hence crucial to assessing the effects and shortfalls of the recent energy development interventions and properly inform policymakers and energy-sector practitioners.

The objective of this study was, hence, to quantify and empirically analyse the current patterns of rural household energy consumption and the share of energy from modern and renewable sources in the rural household energy mix and its implications for energy transition in rural Ethiopia. Specifically, the paper seeks to address:

i) How much energy does the average rural household consume? And what is the share of energy from renewable and modern sources?

ii) Has the rural household heavy reliance on biomass fuels and kerosene declined as a result of access to modern and renewable energy sources and technologies?

iii) What is the prospect of energy transition for cooking and lighting end-uses in rural southern Ethiopia?

2. Materials and Methods

2.1. Study areas and sampling

The study was carried out in four rural districts of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia namely: Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya (Figure 1). Geographically, SNNPRS lies between Latitudes 4°43' – 8°58' North and Longitudes 34°88'- 39°14' East. Administratively, the region is divided into 14 zones (provinces) and 4 special *woredas* (districts), comprising of a total of 137 rural districts and 22 urban administrations [CSA, 2013]. The districts are further sub-divided into *kebeles* (neighbourhoods), the smallest administrative units of Ethiopia. The total population of the region was estimated to be 19. 2 million in 2017, of which 90% were rural inhabitants composed of 2,743,502 households in 3,709 *kebeles* and 10 % were urban dwellers made up of 367,493 households in 324 *kebeles* (CSA, 2013). Out of the total 9 regional states in Ethiopia, the SNNPRS was selected for this study for three reasons. First, it is one of the four regional states in Ethiopia where rural alternative and renewable energy development interventions first began. Second, SNNPRS is home to some of Ethiopia's last remaining natural forests; and third, the region is characterized by diverse agro-ecology, resource endowment, cultures and livelihood patterns.

A multi-stage stratified random sampling approach was used to select sample districts and sample households for the study. In the first stage, 23 rural districts (from the total of 137 rural districts/*woredas* in the SNNPRS); where active deployment of renewable and alternative energy technologies has been taking place since 2008 were identified based on information from the Central Statistical Agency (CSA, 2013) and the regional Mines and Energy Agency. The 23 districts were then clustered into three agro-climatic zones as highland, midland and lowland to capture potential influences of agro-ecology dependent factors on households' energy sources and consumptions. Subsequently, two districts from the highland, one from the midland and one from the lowland stratum were randomly selected. Two districts were selected from the highland because more than 50% of the 23 districts identified fell in this category. Thus, Aleta-wondo and Cheha were selected from the highland stratum; while Boloso-sore and Mirab-abaya districts were selected from the midland and lowland strata respectively.

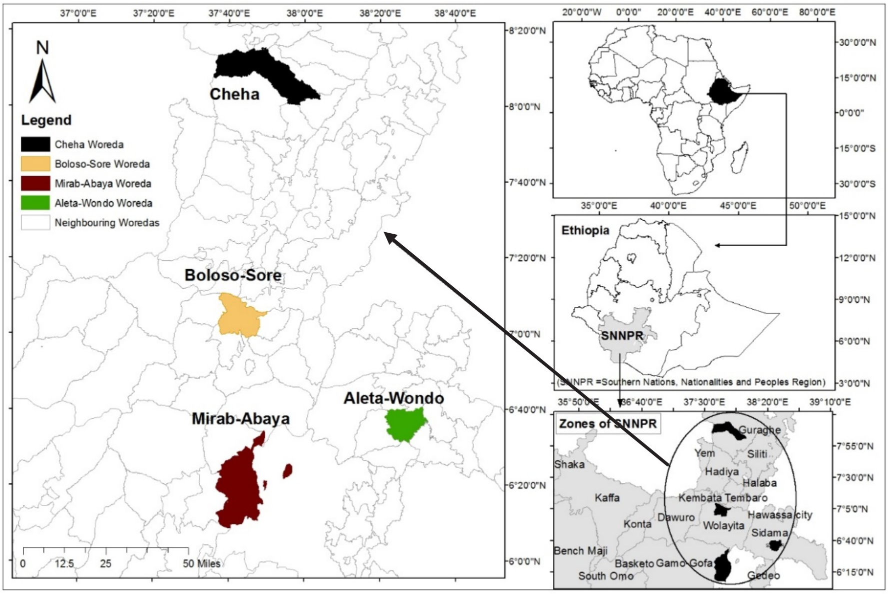

Figure 1. Location map of the SNNPRS region and the study districts (*woredas*)

The total population of Aleta-wondo district in 2017 was estimated to be 187,957 made up of 33, 738 households; and that of Cheha district was 122,770 composed of 24,554 households. The estimated total population of Boloso-sore district in 2017 was 187,558 comprised of 36,410 households and that of Mirab-abaya district was 90, 508 composed of 12,784 households (CSA, 2013). Accordingly, in the second stage, a representative sample size for the study was calculated at 95% confidence level, 4% precision level (for large sample size and smaller allowable error between sample estimates and population values) and p = 0.5 (for unknown population proportion/the most conservative/largest sample size) following Cochran (1977).

$$N = \frac{(z^2 \boldsymbol{\alpha}/_2)\,(p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\ .\ (0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:

N= is the desired sample size

P = 0.5 is the assumed population proportion expected to have access to renewables

e= 0.04 is the desired precision (or margin of error) at 4%

$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size was determined at 660. Subsequently, the total sample size was distributed to the four sample districts selected by using the probability proportional to the household size (PHS) method. Hence, of the total 660 sample households, 207 were allotted to Aleta-wondo district, 224 to Boloso-sore, 151 to Cheha and 78 to Mirab-abaya districts. In the third stage, three *Kebeles* (cluster of villages) were randomly chosen in each district and the sample size allotted to each district was distributed to the three selected *Kebeles* by using the PHS method. Finally, a random selection of sample households was made from a complete list of all the households in each *Kebele* by using a lottery method. A list of all the households in each *Kebele* was obtained from the local *Kebele* administrations.

2.2. Data sources and collection methods

2.2.1. Household surveys:

A cross-sectional survey was conducted using semi-structured questionnaires, which were administered through a face-to-face interview by the researchers and trained data enumerators. The survey questionnaires were designed based on the objectives of the study and review of relevant literature. Prior to the actual survey, preliminary studies were conducted in each sample district, and information was gathered on household energy sources, access to electricity, distributions of renewable energy technologies such as solar PVs, biogas, and ICSs as well as energy markets. This was followed by hiring and training of data enumerators in each district. A pretesting of the questionnaires was conducted on 24 randomly chosen rural households in the study areas. The results from the pre-tests were used to enrich and fine-tune the survey instruments.

Finally, the actual survey was conducted between January and December of 2018 in such a way that sample households identified in each district were randomly assigned to the four seasons in Ethiopia to liquefy potential effects of seasonality on fuel availability and consumption. Data gathered from the survey include socio-economic characteristics, energy sources and consumption quantities, fuel types and end-use devices, prices and power ratings of technologies, frequency of use as well as households' perspectives on benefits and barriers of use of the different energy technologies.

2.2.2. Direct energy consumption and technology use measurements

To accurately estimate the energy consumptions of sample households and minimise potential bias from the self-reported survey data, a direct measurement of the actual fuel consumption of 96 households (15% of the total sample size) from within the total 660 samples was carried out for two consecutive weeks. These 96 households involved in the direct energy consumption measurement were randomly chosen from the four study districts such that 24 were biogas owners, 24 ICSs users, 24 were solar users. The remaining 24 were non-users of renewable energy technologies. To accurately measure the energy consumptions of households, first, the most common local fuel supply modes were identified for each fuel type including animal backloads, human-back/head loads and bundles for fuelwood; small to large bags for charcoal, agr-residues and dung-cakes; and 0.33 to one litre (L) bottles for kerosene. Afterwards, a sufficient number of samples were taken for each fuel supply mode from local markets, fuelwood collectors, retailers, and consumers; and average weights and volumes were determined. Subsequently, the fuelwood, charcoal, agri-residues, dung-cakes, and kerosene oil consumption of the 96 households were directly measured daily for two weeks. Energy consumptions of the households from biogas, grid electricity, and solar were estimated separately with the help of local technicians as presented in the data analysis section. The data collected from the direct measurements were then used to establish average energy consumption benchmarks and triangulate the self-reported survey data, and to later convert energy consumption quantities reported in local units to standard units.

2.2.3. Key informant interviews:

Along-side the household surveys and direct measurements, key informant interviews were conducted with a total of 24 purposively selected informants. The key informants consisted of district and regional level renewable energy and technologies development and promotion professionals; community leaders; selected male and female household heads; NGOs; local fuelwood collectors, charcoal and kerosene sellers, and retailers. In addition to the data collected through the above methods; relevant secondary data were gathered from several reports of various organizations working in the Ethiopian energy sector as well as published and unpublished research works.

2.3. Data analysis and interpretation

2.3.1. Descriptive statistics and Analysis of Variance (ANOVA)

Descriptive and cross-tabulation statistics were used to summarize energy sources by fuel types and end-uses, as well as per capita and annual household energy consumption quantities and the share of energy from renewables in the total household energy use. A univariate (ANOVA) and Multivariate Analysis of Variance (MANOVA) were employed to test the significance of variations in mean household consumption quantities between sample households in the four study districts for some of the most important energy sources and overall energy consumptions.

2.3.2. Quantitative analysis of household energy consumptions

Solid biomass: since separate accounting of household fuel consumption for cooking and baking end-uses was difficult for practical reasons; total household consumption of fuelwood, charcoal, agri.-residues, and dung cakes were quantified on daily and weekly basis separately, and extrapolated to monthly and annual bases.

Kerosene/paraffin: The weekly and monthly kerosene consumption of households was estimated based on the daily kerosene use data from the direct measurements and data collected from the surveys. The weekly and monthly consumptions were then extrapolated to annual consumptions.

Grid-electricity: household electricity consumption was estimated on a monthly basis in two steps. Households who have the Ethiopian Electric Utility (EEU) meter installed were first identified and the monthly electricity consumption was recorded for the last three months from the EEU bills. The average monthly electricity consumption/meter was then determined in kWh. In the second step, all households that share each EEU meter (plus the owner) were counted and the average monthly electricity consumption calculated was divided into the number of households sharing the meter. This is because over 70% of the households that are connected to the grid do not have a private meter but access the grid through shared meters. Although this method of accounting may not fully capture the electricity consumption variations within the 2 to 5 households that share a meter, it provides reliable estimation of electricity use at mini-cluster levels, and comparisons of electricity consumption across districts will remain unaffected.

Biogas: Estimation of household biogas consumption on a daily and annual basis was carried out based on our recent work in the same four districts. Following the methods suggested by IRENA (2016, p. 14), we estimated that the average total biogas produced and consumed from a functional digester (typically 6m^3 digester capacity) was about 0.61m^3/day. The summary table of the daily biogas production and use estimation from 21 operational plants in the four study districts is presented in Appendix I.

Solar energy: Based on IEA's (2012) simple classification, three types of solar energy technologies were identified in the study areas: 1) solar PicoPVs (mostly lanterns) with PV power generation capacity of up to 10 Wp (watt peak); 2) solar home systems (SHS) with PV capacity of 10Wp to 200 Wp, and 3), institutional PV systems with PV capacity of above 200 Wp. Accordingly, the annual energy (electricity) output from each solar PV system was calculated following Nelson and Starcher (2015) equation as:

$$E_a = f_d * H_a * P_{mod} \qquad (2)$$

Where: E_a is the annual electricity output of the solar PV in kWh, f_d is the derater factor or the performance ratio of the solar PV (typically 0.6 – 0.75), H_a is the average annual radiation and P_{mod} is the rated power of the solar PV in kWh. In this study, the value f_d was taken at 0.75 following Quaschning (2019) for an average system, and the value for the annual radiation H_a in the study area was taken 1800 following Tilahun et al (2017).

The average household energy consumptions from the various sources and fuels were finally converted to a common unit of Megajoules (MJ) based on their energy using their corresponding conversion factors

Table 1. Energy content of different fuels in Ethiopia and the developing world in MJ

Fuel	Unit	Energy content (MJ/Unit)	Data source
Fuelwood (air-dried)	Kg	15.00	Hall et al., (1994)
Charcoal	Kg	29.00	Guta (2012)
Agricultural residues	Kg	14.40	Negash et al. (2017)
Dung cakes (10% MC)	Kg	9.00	Barfuss et al. (2013)
Kerosene (wick lamps)	Litre	35.36	Smith et al. (2000)
Biogas	m^3	20.00	Gwavuya et al. (2012)
Electricity	kWh	3.60	Foley (2015)

3. Results and discussions

3.1. Demographic and socio-economic characteristics of the households

Of the 660 total sample households determined for the study, 605 completed the survey. Data from the remaining 55 were either incomplete or hugely inaccurate when cross-validated and hence excluded. The overall response rate was thus 91.70%. Except in very few cases, the respondents were household-heads. Table 2 presents the descriptive statistics of some of the most important characteristics of the sampled households. As shown in Table 2, 189 (31%) of the households surveyed were drawn from Aleta-wondo district, 204 (34%) from Boloso-sore, 134 (22%) were from Cheha and 78 (13%) were from Mirab-abaya districts. Of the total 605 rural households surveyed about 84.13% were headed by males and the remaining 15.87% were headed by female heads.

Table 2. Descriptive statistics of sample households

Variables		Statistic	Study areas (districts)				Total Mean (N = 605)	S.E.
			Aleta-wondo	Boloso-sore	Cheha	Mirab-abaya		
Number of sample households		Num	189	204	134	78	605	
Gender of HH head	Male	Num	162	181	108	58	509	
	Female	Num	27	23	26	20	96	
Age of HH head		Mean	50.65	43.95	49.71	51.53	48.30	10.92
Education level of HH head		Mean	5.86	4.62	3.97	3.55	4.73	3.77
HH size (total)		Mean	6.76	7.00	4.34	6.29	6.24	2.38
Family members < 15 years		Mean	3.21	3.63	1.62	1.64	2.80	1.84
Main occupations	Cash cropping	%	50.00	16.20	22.20	45.00	32.00	
	Food cropping	%	18.50	42.70	25.80	9.00	26.00	
	Crop-livestock mixed farming	%	27.70	21.80	19.60	29.00	24.00	
	Off-farm activity	%	1.60	19.03	22.70	8.80	13.00	
	Private business	%	2.94	1.00	10.10	9.00	5.00	
Total landholding in hectares		Mean	0.53	0.88	0.65	0.74	0.70	0.64
Cattle heads size		Mean	3.06	3.44	2.85	5.83	3.50	2.36
Gross annual cash income ETB		Mean	28358	16579	17184	38123	22155	22350
Round-trip walking distance to wood source, minutes		Mean	52.8	49.6	42.8	152.8	62.4	75.2
Round-trip walking distance to market, minutes		Mean	106.8	108.4	104	100.4	105.2	35.2
Grid-connected		%	40.74	8.82	29.85	75.64	32.06	
Access to credit service		%	55.32	21.57	22.39	43.59	35.04	

Source: Own field survey, 2018.

The average age of household-heads is 48.30 years, and the average educational status of household-heads, measured in terms of the number of years of schooling completed, was 4.73. The average total family size of the households is 6.24 persons per household, but the figure varies between 4.34 in Cheha district and 7.0 persons in Boloso-sore. On average, there are 2.8 persons (45% of the total family size) per household under the age of 15 years, but this figure varies across the four districts between the lowest 1.62 in Cheha and the highest 3.63 in Boloso-sore. As will be seen later, these variations in household size are associated with fuelwood consumption levels owing to its influence on labour availability for fuelwood collection.

Concerning the major occupation (source of livelihood), generally, most households are engaged in multiple occupations. Nevertheless, 32% stated cash-crops growing such as coffee, khat (*C. edulis*), and banana; 26% food crops production mainly 'Enset'- Ethiopian false banana (*E. ventricosum*), cereals and root-crops, and 24% crop and livestock mixed-farming. In contrast, 13% earn their living from off-farm activities including daily labour and forest products collection (fuelwood, timber, and non-timber products), and 5% are engaged in small private businesses. However, notable variations were observed across the four districts in terms of the importance of these occupations as livelihood sources. A higher number of households in Aleta-wondo and Mirab-abaya districts were engaged in cash cropping than in the other two districts.

The average landholding size per household is 0.7 ha with the highest holding (0.88 ha) in Boloso-sore and the lowest (0.53 ha) in Aleta-wondo. The average cattle heads size per household is 3.50, with the highest holdings in Mirab-abaya (5.83) and the lowest in Cheha (2.85) districts. According to Zeleke and Getachew (2017) and the key informants interviewed, the recent decline in cattle-holdings in Mirab-abaya, traditionally a cattle-herding district, was largely due to the prevalence of deadly cattle diseases coupled with frequent droughts that have led to the catastrophic loss of large cattle population in the district. The average gross annual cash income per household was estimated to be ETB 22,155 (≈ US$ 815 in August 2018). However, household income varies greatly across the four districts with the highest income in the mostly cash-crops growing districts of Mirab-abaya (ETB 38,123) and Aleta-wondo (ETB 28,358) compared with the largely food-crops (Enset *(E. ventricosum)*, cereals, and root-crops) producing districts of Cheha (ETB 17,184) and Boloso-sore (ETB 16, 579), respectively.

About 55.3% and 43.6% of the households in Aleta-wondo and Mirab-abaya districts, respectively have access to credit services (mostly from Omo Micro Finance) whereas only 22.4% and 21.6% of households in Cheha and Boloso-sore, respectively had access to credit service. The average walking distance between the households' home and the nearby wood source (forests and woodlands) was 62.4 minutes (round-trip) but varies markedly between 42.8 minutes in Cheha district and 152.8 minutes in Mirab-abaya. The average walking distance between the household's home and the local market was 105.2 minutes (round-trip) with small variations between the shortest 104.4 in Mirab-abaya and the longest 108.4 minutes in Boloso-sore districts.

According to the survey data, about 32% of the sample households are connected to the national grid (Ethiopia's main electricity supplier). However, there was a stark disparity in access to electricity among households in the four districts. More than 75% of the sampled households in Mirab-abaya were connected to the grid electricity whereas only 8.8% of the households in Boloso-sore were connected to the grid. While our sample average of 32% grid electricity coverage is in congruence with the World Bank's recent data of 31% electricity connection for rural households in Ethiopia (SE4ALL, 2017), the high connection rate observed in Mirab-abaya district could be due to its closeness to Arba-minch city and the major power line crossing the district.

With respect to biogas use, it was found that only 5.3% (32) of the sampled households have adopted the technology despite its introduction in Ethiopia as early as 1979 (SNV, 2008). Moreover, of the 32 biogas plants examined during the study, only 21 (65.7%) were fully or partially functional in 2018. According to the key informants interviewed, the loss of cattle due to deadly diseases and the subsequent lack of feedstock (cow-dung) particularly in the lowland district of Mirab-abaya; shortage of water and labour, and the lack of maintenance services were among the main factors for the under-utilization and abandonment of some biogas plants installed in the areas. In contrast, the adoption and use of stand-alone solar photovoltaic (PV) technologies such as solar home systems (SHS) and PicoPVs (lanterns) is gaining a foothold in the region within a short period of introduction (Padam et al., 2018). As a result, 22.64% (137) of the sampled households were found to have at least one SHS or lantern. Likewise, the use of improved biomass cookstoves (ICSs) is growing in the region and Ethiopia at large. As such, 22 % (133) of the sampled households were found owning at least one type of ICSs.

3.2. Household energy sources and fuels types by end-use

Rural household energy use in Ethiopia can be broadly grouped into three categories: cooking, baking, and lighting. Cooking comprises of primarily cooking of daily meals, boiling of water, and preparation of coffee and tea. Baking involves, baking of [2]'Injera' and '*Kocho*'. Lighting is mostly limited to indoor lighting services.

3.2.1. Energy sources for cooking

A range of fuels, mainly biomass fuels, are used for household cooking in rural Ethiopia. The majority, 90.74%, of the households in this study depend on fuelwood as their main energy source for cooking (Figure 2), followed by agri-residues 3.14%, charcoal 2.31%, and biogas 1.98%. In contrast, 1.16% use electricity and 0.66% dung cakes for cooking. This means almost 97% of the households depend on traditional solid biomass fuels for cooking. As noted earlier, the main reason that only 1.98% (of the 5.3%) biogas owners are using biogas as the main energy source for cooking is that many of the biogas plants constructed in the study areas have malfunctioned. On the other hand, the data from the direct energy consumption measurements and kitchen cooking observations showed that some of the households do use multiple (mix) cooking fuels for complementarities.

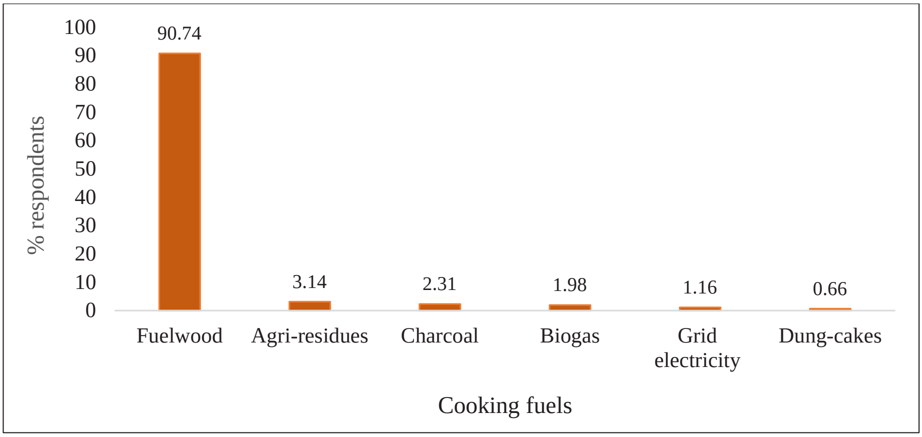

Figure 2. Distribution of households by primary sources of energy for cooking

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[2] *Injera* and *Kocho* are thin round flatbreads much like large pancakes consumed as staple foods in much of Ethiopia and the SNNPRS, respectively.

According to the Ministry of Water and Electricity (MoWE, 2012) in 2004, about 0.2% of rural households in Ethiopia (at the national level) were using charcoal for cooking. Though empirical data on past trends of rural household charcoal use in the SNNPRS is not available, comparing our finding of 2.3% with the 0.2% reported at the national level in 2004 may hint an increase in the use of charcoal as cooking fuel in rural Ethiopia. This supports the findings of Guta (2014) who estimated that approx. 5% and 4% of rural households in Ethiopia use charcoal and agri. residues respectively as cooking fuels.

The above results generally corroborate the findings of several previous studies (CSA, 2012; Guta 2014; Tucho, 2016; Mondal et al, 2018) that reported the dependence of almost all rural households in Ethiopia on traditional biomass fuels as primary energy sources for cooking. As such, this study finds little evidence of a significant decline in the proportion of rural households that rely on traditional solid biomass fuels for cooking. Nonetheless, the fact that 1.98% and 1.16% of the sample households are using biogas and electricity respectively for cooking signals the possibility of future use of biogas and electricity for cooking in rural Ethiopia subject to the functionality the biogas plant and availability of affordable and reliable electricity supply.

3.2.2. Energy sources for baking Injera and other bread (*kocho*)

Injera and *Kocho* baking are highly energy-intensive. According to some estimates (e.g. Mulugeta et al., 2017; Kebede and Kiflu, 2014) '*Injera'* baking accounts for more than 50% of the total household energy demand in Ethiopia. Analysis of household energy sources for baking *Injera*/*Kocho* in this study (Figure 3) indicated that the vast majority (95.2%) of the households depend on fuelwood as the primary fuel for baking *Injera* and *kocho* or other bread while 3.31% use agri residues. By contrast, only 0.83% and 0.66% of the sampled households use electricity and dung cakes as primary energy sources for '*injera'* baking respectively. Two major obstacles were identified for the limited use of electricity for cooking and baking end-uses by rural households. The first is the high cost of electrical appliances such as electric cooking stoves and electric baking stoves (locally known as 'Electric '*Mitad'*) compared to the purchasing power of rural households. From our market assessments in the study areas, the average price of a regular 'Electric baking *Mitad'* ranges between ETB 4000 and 6000 equivalent to US$150 – $225.

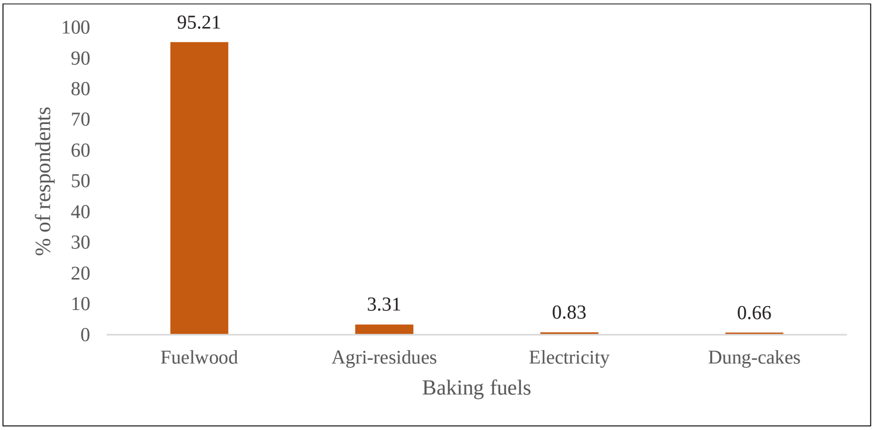

Figure 3. Distribution of households by primary sources of energy for baking *Injera*

The second and equally important barrier is the unreliability of electricity supply in the country with frequent power outages for several hours a day, discouraging households from cooking and baking with electricity. Another important reason could also be that some households are not aware that it is actually cheaper (based on our assessment) to use electricity than fuelwood and/or charcoal for cooking especially if the fuelwood and charcoal are to be obtained from buying in local markets.

3.2.3. Energy sources and fuels for lighting

Analysis of primary energy sources of survey households for lighting (Figure 4) showed that about 50.08% of the households depend on kerosene and traditional kerosene wick lamps; 28.93% grid-electricity, 19% use solar PVs/lanterns, and 1.98% on biogas. In retrospect to the 70% to 80% kerosene dependent rural households for lighting in the SNNPRS reported in 2010 (MoWE, 2012), the present figures may suggest a substantial decline in the use of kerosene as the primary lighting energy source in rural Ethiopia. This can be attributed to the increase in rural access to electricity and the dissemination of solar technologies. Compared with the national electricity coverage of 6.6% for rural households in Ethiopia in 2010 (MoWIE, 2013), the present rate of grid connection of 32% in the study areas signifies major progress for the Ethiopian rural energy sector.

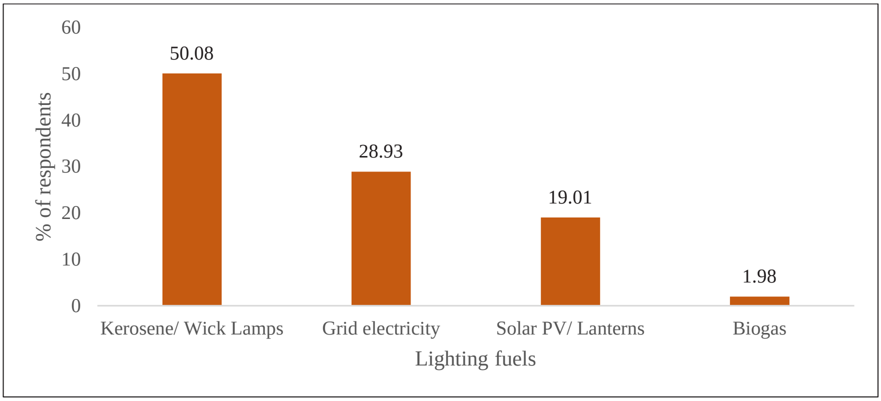

Figure 4. Distribution of households by primary source of energy for lighting

However, the study also finds that despite the grid connection and adoption of solar PVs and lanterns, a significant proportion of the rural households still use kerosene, dry-cell batteries, and candles as secondary and back-up lighting fuels. In this regard, we found that about 15% of the total sampled households use a combination of dry-cell batteries (hand-torches) and kerosene for lighting; close to 13% use grid electricity and kerosene; and about 7% use a combination of solar power and kerosene for lighting. This shows that despite the increased access to electricity and solar PVs, the supply of modern and clean energy in rural Ethiopia is still unreliable and insufficient. As a result, even though 32% of the sampled households are connected to the grid, the electricity supply does not meet their basic energy needs due to severe power shortages, frequent outages, and intermittency problems. Evidently, out of the 194 sample households that are connected to the grid, only 175 use electricity as the primary energy source for lighting. The energy shortage for solar users, on the other hand, is mostly associated with the limited capacity of the PVs systems, intermittency of the power generation, low-quality of the products, and lack of maintenance services.

Overall, analysis of the survey data for household energy sources reveals that modern fuels including electricity are not yet common sources of energy for cooking and baking; rather the overwhelming majority of the rural households continue to depend on traditional biomass fuels particularly fuelwood as primary cooking and baking fuel. On the bright side, rural household energy use for lighting is steadily embracing renewable, clean, and modern fuels such as electricity, solar, and to less extent biogas.

3.3. Household energy consumption patterns

3.3.1. Solid biomass energy consumption

3.3.1.1. Fuelwood

Based on the data from the direct energy consumption measurements and household surveys, the average monthly, per capita, and annual biomass fuels consumptions of the sample households were estimated, and the results are discussed hereafter. According to our estimates (Table 3), the average fuelwood consumption of a rural household in the study area is about 104.62 kg/week; which corresponds to an average consumption of 418.48 kg/month and 5021.8 kg/year per household while the per capita fuelwood consumption was estimated to be 913.52 kg/year. These results generally support the findings of previous studies by Guta (2014) and Tucho (2016) which estimated that the average annual fuelwood consumption of a rural household in Ethiopia to be 4600 kg, and between 4000 kg and 5000 kgs per year respectively.

Table 3. Household fuelwood consumption in the study areas

District	Per week (kg)	Per month (kg)	Per capita (kg/year)	Per year (kg) (SE)
Aleta-wondo	128.43	513.71	989.63	6164.57 (2899.93)
Boloso-sore	121.87	487.49	927.69	5849.88 (3298.37)
Cheha	74.69	298.78	1038.38	3585.35 (2052.79)
Mirab-abaya	53.22	212.90	477.57	2554.77 (1435.14)
Mean	104.62	418.48	913.52	5021.80
S. E	65.70	262.78	464.11	2692.0

*Numbers in parenthesis are standard errors (SE)

However, analysis of variations in mean fuelwood consumption quantities among the rural households in the four districts (groups) showed significant differences (Table 4). Notably, the average fuelwood consumption per household is highest in Aleta wondo (6164 kg/year) and lowest in Mirab-abaya (2554 kg/year). The large value of F statistic of the ANOVA analysis (the ratio of between and within group mean squares) shows that the variation in household energy consumption between districts is much higher than the variation within the districts. This means that the location (district) of the household does affect the household’s fuelwood consumption significantly.

The reason is likely due to differences in the availability and accessibility of fuelwood between the districts. According to Abebe (2005), most rural households in Sidama zone where Aleta-wondo is one of the districts, collect fuelwood from their homegardens that is enough to meet their basic domestic cooking energy demand. On the other hand, the lowest household energy consumption in Mirab-abaya district could be attributable to the increasing scarcity of fuelwood following years of 'illegal' charcoal production that supplied markets as far as the capital Addis Ababa some 505 km North.

Table 4. Results of the ANOVA for mean annual household fuelwood consumption between the four study districts (groups)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.91E+11	3	9.71E+10	50.562	3.7E-09	2.619
Within Groups	1.15E+12	601	1.92E+09			
Total	1.45E+12	604				

By contrast, the average per capita fuelwood consumption is the highest 1038 kg/year in Cheha district and lowest 477 kg/year in Mirab-abaya. This could be due to the lower average household size in Cheha district and conversely higher household size in Mirab-abaya relative to the total fuelwood consumed per household. Nevertheless, the large standard error values of the mean annual fuelwood consumptions in each district (see the last column in Table 3) in particular for Aleta-wondo and Boloso-sore indicate the presence of sizable variability in the quantity of fuelwood consumed among households within each district. This could be due to variations in socio-economic and demographic characteristics of the households within each district.

Analysis of household fuelwood consumption by primary source (Figure 5) showed that 55% of the households surveyed collect fuelwood from 'open access' state/communal forests and woodlands ('for free') despite these forests are protected by law. About 25% of the sampled households reported collecting fuelwood from their farmlands, woodlots and homegardens. In contrast, 11.25% reported buying fuelwood from local markets and 8.5% do a combination of collecting and buying.

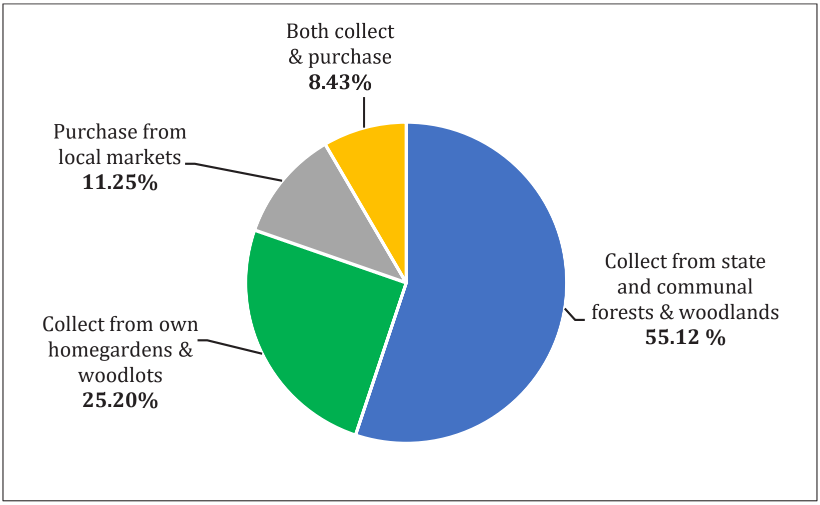

Figure 5. Distribution of total household fuelwood consumption by source

Despite the sizable percentage of households who stated to collect fuelwood from own sources, the findings revealed that the quantity of fuelwood actually collected from own wood sources is very small compared to the fuelwood collected from 'open access' state and communal forests. From our data analysis, it was found that the average quantity of fuelwood collected from communal and state forests per household per year was about 4,248 kg (84.6%) while fuelwood collected from own homegardens and farmland was only 525 kg (10.46%). The small quantity of fuelwood from own homegardens could be partly because districts like Mirab-abaya are mostly dependent on state and communal forests and woodlands for fuelwood whereas districts like Aleta-wondo can meet a large portion of their fuelwood demand from their own homegardens.

The average quantity of fuelwood purchased by a household is 248 kg/year, i.e. roughly 5% of the total 5021.8 kg consumed. The average weight of a human-load of fuelwood (headload and backload) is 27.26 kg and the average price of fuelwood was ETB 2.82/kg. Since almost all the fuelwood supplied to local markets is collected from 'open-access' forests, the results imply that nearly 90% (4496.8 kg out of the 5021.8 kg) of the total household fuelwood consumption is met by these state/communal forests. This shows that Ethiopia's state/communal forests suffer the most from the increasing demand for woodfuels, effectively undermining the country's climate change mitigation potential and the valuable ecosystem services these forests provide.

3.3.1.2. Agricultural residues

Unlike in much of the northern and central highlands of Ethiopia where crop residues and dung cakes make up a significant part of the rural household energy mix (Negash et al., 2017; Gebreegziabher, 2007; Mekonnen, 1999), their utilization as primary energy sources is generally limited in the SNNPRS. This is perhaps due to two reasons. First, out of the nine regional states in Ethiopia, the SNNPRS is the region with the fourth largest forest cover with an estimated 12% forest coverage, which accounts for 9.5% of the total forest area of the country (based on FAO forest classification) (FAO, 2015). This relative better woody biomass endowment of the region means better access to woody biomass fuels in relatively short distances as was reported by Shanko and Lakew (2011). Second rural livelihoods in much of the SNNPRS depend on Coffee and Enset-based agroforestry practices; cash crops (coffee, khat, banana), and root crops as opposed to the dominantly cereal crop-based agrarian systems in North and central Ethiopia. As such, households in the SNNPRS are relatively better-off economically and could afford to buy fuelwood, charcoal, and other alternative energy sources.

From our analysis (Table 5), the average monthly and annual household consumptions of agricultural residues (crop residues; coffee, Enset, and banana residues) for domestic energy purpose was estimated at 44.37 kg and 532.46 kg, respectively while the average per capita consumption was calculated at 81.82 kg/year.

Table 5. Agricultural residues consumption of sample households in the study areas

District	Per week (kg)	Per month (kg)	Per capita (kg/year)	Per year (kg) (SE)
Aleta-wondo	8.77	35.08	62.20	421.00 (270.89)
Boloso-sore	20.15	80.60	138.18	967.19 (196.41)
Cheha	5.00	20.00	55.00	240.00 (321.79)
Mirab-abaya	3.50	14.00	28.00	168.00 (199.35)
Total Mean	11.09	44.37	81.82	532.46
S.E	6.57	26.27	41.21	315.24

*Numbers in parenthesis are standard errors (SE)

However, as the mean consumption values in Table 5 and the ANOVA analysis in Table 6 show, there is a significant variation in mean annual household consumption of agri-residues between households in the four study districts. In the relatively low-income and largely agrarian district of Boloso-sore, energy from agri.- residues still constitutes a considerable portion of the household energy use. Conversely, the consumption of agri residues is minimum in the mostly cash-crops growing district of Mirab-abaya.

Table 6. Results of the ANOVA for mean annual agri residues consumption between the four study districts (groups)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.1E+08	3	1.7E+08	13.199	2.3E-08	2.619
Within Groups	7.75E+09	601	12889343			
Total	8.26E+09	604				

Although not statistically significant, the large values of standard errors of mean annual agri-residue consumptions in each district (Table 5) notably for Aleta-wondo and Cheha districts may suggest considerable variability in agri residue use among the households within each district. This could be due to local differences in access to other fuels, and economic and demographic characteristics of the households within the districts.

3.3.1.3. Charcoal

Charcoal has long been one of the major cooking fuels of urban households in Ethiopia along-side fuelwood and kerosene (Mondal et al., 2018; Mekonnen and Köhlin, 2009). However, its consumption in rural areas is a recent phenomenon. There could be two explanations for that. One is the influence of spill-over effects from rapid urbanization in peripheral areas with an increasing supply of charcoal burning stoves in the market. The second is perhaps the increase in disposable income of rural households to afford expensive but convenient fuels such as charcoal. As noted by Gupta and Köhlin (2006), availability and ease of use are important factors for household fuel choice. This is also evidenced by the results of our analysis (see Table 7), where high-income households in the largely banana-growing district of Mirab-abaya have the highest average charcoal consumption of 192.72 kg/household/year.

Table 7. Charcoal consumption of households in the study areas

District	Per week (kg)	Per month (kg)	Per capita (kg/year)	Per year (kg) (SE)
Aleta-wondo	1.43	5.73	10.17	68.72 (51.89)
Boloso-sore	0.53	2.14	3.66	25.65 (45.01)
Cheha	1.73	6.91	19.11	82.93 (61.77)
Mirab-abaya	4.02	16.06	30.64	192.72 (91.99)
Total Mean	1.53	6.11	11.75	73.33
S.E.	2.95	11.77	22.92	121.26

*Numbers in parenthesis are standard errors (SE)

Counter-wise, the low-income households in the mostly agrarian district of Boloso-sore have the lowest average charcoal consumption of 25.65 kg per household per year. And this variation in annual charcoal consumption among households in the four districts is statistically significant as shown by the results of the ANOVA analysis in Table 8.

Table 8. Results of the ANOVA for mean household charcoal consumption between the four study districts (groups)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.34E+09	3	4.46E+08	6.688	0.0001	2.619
Within Groups	4.01E+10	601	66717315			
Total	4.14E+10	604				

Overall, the average charcoal consumption per household across the four districts was estimated at 73.33 kg/year and the per capita consumption was about 11.75 kg/year. The average weight of a medium bag of charcoal in the local markets was about 23.66 kg and the average price of this medium bag charcoal including local transport was ETB 150. From this, the average price of charcoal per kg was estimated at ETB 6.34. However, from our market studies this price increases almost by 50% in urban areas resulting in the average price for the same weight bag of charcoal to be between ETB 230 and 250 which corresponds to ETB 9.7 – 10.6 per kg.

3.3.1.4. Animal-dung cakes

Contrastingly, the average monthly and annual household consumptions for dung cakes were estimated at 1.45 and 17.45 kg, respectively, and the per capita consumption of dung cakes was 2.86 kg/year (Table 9). These results imply that dung cakes are the least consumed biomass fuels in the study areas.

Table 9. Animal-dung cakes consumption of households in the study areas

District	Per week (kg)	Per month (kg)	Per capita (kg/year)	Per year (kg) (SE)
Aleta-wondo	0.21	0.85	1.50	10.15 (20.02)
Boloso-sore	0.53	2.12	3.63	25.42 (43.96)
Cheha	0.32	1.28	3.53	15.40 (23.84)
Mirab-abaya	0.37	1.48	2.97	17.80 (33.90)
Mean	0.36	1.45	2.86	17.45
S.E.	0.11	0.46	0.85	35.50

*Numbers in parenthesis are standard errors (SE)

One of the main reasons, as explained by the households, for the limited consumption of dung cakes as cooking fuels was its highly valued application as organic fertilizer for *Enset* cultivation and to a lesser extent to banana plantations. This is also evident from the low-level of use of dung-cakes as energy sources in Mirab-abaya district despite the relatively higher cattle-heads size per household. Yet, in the relatively low-income and largely agrarian areas such as the Boloso-sore district, dung cakes still play some role in the household energy mix. A rural household in Boloso-sore consumes on average 25.42 kg of dung cakes per year as part of the household energy mix.

3.3.2. Petroleum products (kerosene) consumption

The consumption of petroleum products in rural Ethiopia is dominated by kerosene (paraffin) and it is predominantly used for lighting services with traditional kerosene wick lamps (known as *Kuraz*). From our analysis of the survey data, the average monthly and annual kerosene consumptions per household were estimated at 2.50 L and 30.09 L, respectively, and the per capita kerosene consumption is estimated at 4.82 L/year.

Table 10. Kerosene consumption of households in the study areas

District	Per week (L)	Per month (L)	Per capita (L/yr)	Per year (L) (SE)
Aleta-wondo	0.396	1.58	2.81	18.99 (23.91)
Boloso-sore	1.232	4.92	8.44	59.12 (30.59)
Cheha	0.292	1.17	3.23	14.02 (23.15)
Mirab-abaya	0.181	0.72	1.38	8.68 (18.47)
Mean	0.627	2.50	4.82	30.09
S.E.	0.94	3.78	6.00	45.34

*Numbers in parenthesis are standard errors (SE)

Examining the average kerosene consumptions by district, however, indicated large and statistically significant variations between the four districts as shown by the results of the ANOVA analysis in Table 11. Evidently, the average monthly and annual kerosene consumptions of a rural household was highest in Boloso-sore district with calculated values of 4.926 L and 59.12 L, respectively; and lowest in Mirab-abaya with monthly average consumptions of 0.72 L and annual consumptions of 8.68 L.

Table 11. Results of the ANOVA for mean household kerosene consumption between the four study districts (groups)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.32E+08	3	1.11E+08	134.6817	9.7E-17	2.619
Within Groups	4.94E+08	601	821661.8			
Total	8.26E+08	604				

The results confirm that, in Mirab-abaya district where more than 75% of the sample households are connected to the grid, annual kerosene consumption per household is 50.44L (85%) less than the average kerosene consumed by households in Boloso-sore where only 8.8% of the households have access to the grid. In the same pattern, in Cheah district where 47% of the sampled households have adopted SHSs and/or lanterns, the kerosene consumption per household is 45L (76%) less than the amount consumed in Boloso-sore district (see Table 10). This indicates that recent interventions to improve rural access to electricity and dissemination of solar lighting technologies are enabling the rural households to substitute the toxic and environmentally unfriendly fossil fuels (kerosene) with cleaner and modern lighting energy.

3.3.3. Grid electricity

The Ethiopian Electricity Utility (EEU) is the main supplier of electricity in Ethiopia and 90% of the national power production comes from hydro-power (Mondal et al., 2018). Energy distributed through the national grid is heavily subsidised by the government and according to the new adjusted tariff, the price of electricity for households in 2018 was on about ETB 0.572 (US$ 0.021) per kWh. From the survey data, 29.4% of the total 194 households that are connected to the grid own a private electric (EEU) meter while 70.6% are connected to the grid by sharing from their neighbours. The average monthly and annual electricity consumption of the households were estimated at 15 kWh and 182.43 kWh, respectively, and the per capita consumption was at 29 kWh/year.

Compared with the negligible amount of electricity consumed by rural households in Ethiopia in the 2000s (Barnes et al., 2016), the present average annual consumption of 182.43 kWh electricity suggests promising progress in rural electricity use in Ethiopia. Yet, when compared with IEA's (2014) minimum electricity consumption level of 1, 250 kWh per household per year, the current level of electricity consumption is far below the basic requirement to be considered to have access to sufficient electricity. In this regard, Tucho et al (2014) have also explained that even when there is electricity supply to fulfil the basic household energy demand, not many rural households cook or bake with electricity due to the high cost of electric cooking appliances in rural areas.

Table 12. Household grid-electricity consumption in the study areas

District	Per week (kWh)	Per month (kWh)	Per capita (kWh /year)	Per year (kWh) (SE)
Aleta-wondo	4.34	17.37	30.84	208.46 (279.09)
Boloso-sore	0.42	1.67	2.86	20.04 (123.17)
Cheha	4.47	17.88	49.43	214.51 (426.57)
Mirab-abaya	10.19	40.75	77.74	489.00 (346.68)
Total Mean	3.80	15.20	29.24	182.43
S.E.	8.11	32.44	63.33	389.22

*Numbers in parenthesis are standard errors (SE)

In terms of geographic location, access and use of electricity vary greatly across the four districts. Notably, the average electricity consumption per household is the highest 489 kWh in Mirab-abaya district and lowest 20 kWh in Boloso-sore. This difference in mean annual electricity consumption of sample households among the four study districts is statistically significant as shown by the results of ANOVA analysis in Table 13.

Table 13. Results of the ANOVA for mean household electricity consumption between the four study districts (groups)

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.68E+08	3	56055683	50.795	2.8E-11	2.62
Within Groups	6.63E+08	601	1103621			
Total	8.31E+08	604				

3.3.4. Biogas energy

According to our results estimated from 21 functional digesters (all of which were 6m^3 capacity), in the four study districts, the average daily biogas produced and consumed per household per operational digester was estimated at 0.61 m3 (see Appendix I). Since in all cases the biogas produced is insufficient and hence consumed within 24 hours, the monthly and annual biogas consumptions per household of the total sample households were estimated based on this average daily biogas production and consumption values. Based on this daily use, the average biogas consumptions of the total survey households were estimated at 0.02 m^3/day and 7.78 m^3/year (Table 14).

Table 14. Average household biogas production and consumption in m^3

District	Sample Biogas plants	Operat-ional plants	Average biogas per operat. plant (m3/day)	Total biogas from operat. plants (m3/day)	Average HH consumption (m3/day) (N=605)	Average HH consumption (m3/year) (N=605)
Aleta- W.	12	9	0.725	6.525	0.035	12.601
Boloso- S.	8	6	0.607	3.642	0.018	6.516
Cheha	7	4	0.401	1.604	0.012	4.369
Mirab- A.	5	2	0.562	1.124	0.014	5.260
Mean			0.61		0.02	7.78
S.E.			0.12		0.01	9.23

From our field assessments, it was clear that domestic biogas technology in the SNNPRS is faced with serious problems of malfunctioning and poor performance. As a result, the biogas produced from the few operational plants is not even sufficient to meet half of the daily cooking energy needs of the households. A great deal of the problems is tied to the lack of maintenance services, poor biogas operational practices, shortage of labour and feedstock, and lack of commitment and motivation from the users' side.

3.3.5. Solar energy

From the comprehensive field studies and assessments we made with the help of local solar technicians to every solar user household, the distribution of the solar PV systems by rated power is shown in Figure 6. According to our results, 63% of the solar PV users own PicoPV systems (mostly lanterns) with a power generation capacity of up to 10Wp, 30% own SHSs with power generation capacity ranging from 11Wp to 40 Wp, 5% own SHSs with PV capacity between 41Wp and 100 Wp, and about 2 % own SHSs with power capacity above 100 Wp. As explained by solar users, the preference for lower capacity solar solutions is due to lower prices, ease of use, and portability.

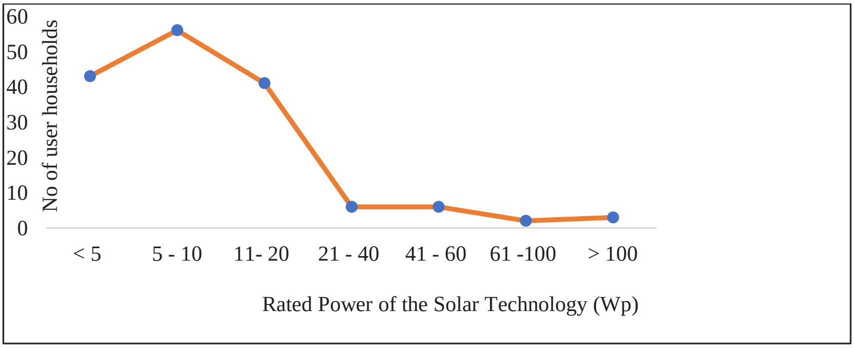

Figure 6. Distribution of solar technologies by power generation capacity

Our estimates for solar energy output from the various solar products using equation 2 indicated that on average, a rural household in the study area consumes 0.396 kWh per month and 4.755 kWh per year. The per capita solar energy consumption was estimated at 0.762 kWh/year. The average solar energy consumption per household was highest in Cheha district (7.8 kWh/year) and lowest in Mirab-abaya district (0.571 kWh/year).

Table 15. Household solar energy consumption in the study areas

District	Per week (kWh)	Per month (kWh)	Per capita (kWh/year)	Per year (kWh) (SE)
Aleta-wondo	0.142	0.568	1.008	6.812 (21.26)
Boloso-sore	0.108	0.432	0.740	5.178 (21.84)
Cheha	0.163	0.651	1.799	7.808 (19.78)
Mirab-abaya	0.012	0.048	0.091	0.571 (1.20)
Mean	0.099	0.396	0.762	4.755
S.E.	0.30	1.19	2.29	14.27

*Numbers in parenthesis are standard errors (SE)

However, as can be seen from the ANOVA analysis results in Table 16, the variation in mean annual solar energy consumption between rural households in the four districts was not statistically significant ($p < 0.05$). This means that there is no enough evidence to suggest that households in the four districts consume a significantly different quantity of energy from solar power. In other words, the difference in household solar energy consumption between the districts (groups) is not stronger than the variability among households within each district. This is despite the substantially higher number of solar adopters and the relatively higher quantity of solar energy consumed by households in Cheha district compared to the other districts. The reason for the relatively higher solar power use in Cheha district is perhaps due to the higher number of solar adopters from the widespread dissemination of solar technologies in the area.

Table 16. ANOVA of mean household solar energy use between the four study districts

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	36874.9	3	12291.63	2.4364	0.0637	2.619
Within Groups	3031995	601	5044.917			
Total	3068870	604				

Overall, statistical analysis of the variations in mean annual energy consumptions of the sample households in the four districts for the various fuel types measured has shown the presence of significant differences as illustrated by the results of the multivariate MANOVA test in Table 17. This indicates that the effect of geographic location (district) and the resultant economic and agro-ecological factors in influencing access, availability and consumption of energy sources of rural households is significant.

Table 17. Results of the Multivariate ANOVA significance tests for overall household energy consumption variations between households in the four study districts (groups)

Criterion	Test Statistic	Approx F	Num	DF Denom	P
Wilks'	0.49700	31.676	15	1648	0.000
Lawley-Hotelling	0.93280	37.043	15	1787	0.000
Pillai's	0.54302	26.477	15	1797	0.000
Roy's	0.84187				

s = 3 m = 0.5 n = 297.5

3.4. Total household energy consumption

Table 18 presents a summary of the average annual total energy consumption of sample households from the various fuels and sources in the four districts. The average annual energy consumptions from the different fuels are then converted to Megajoules (MJ) by using the conversion factors indicated in Table 1 and the results are shown in Table 19.

Table 18. Mean annual household energy consumption from the different sources

District	Fuelwood (kg)	Agri. residue (kg)	Charcoal (kg)	Dung cakes (kg)	Kerosene (Lit)	Biogas (m3)	Electricity (kWh)	Solar (kWh)
Aleta-W.	6164.57	421.00	68.72	10.15	18.99	12.601	208.46	6.81
Boloso-S.	5849.88	967.19	25.65	25.42	59.12	6.516	20.04	5.18
Cheha	3585.35	240.00	82.93	15.40	14.02	4.369	214.51	7.81
Mirab-A.	2554.77	168.00	192.72	17.80	8.68	5.260	488.99	0.57
Mean	5021.80	532.46	73.33	17.45	30.09	7.78	182.43	4.76
S.E.	2692.0	315.24	121.26	35.50	45.34	9.23	389.22	14.27

According to the results in Table 19, the total energy consumption of a rural household was estimated to be 87,172 MJ/year. Examination of the share of the different fuels in the total household energy consumption revealed that fuelwood takes the lion's share accounting for 75, 327 MJ (86.41%). In contrast, energy from agri.-residues constituted 7667.4 MJ (8.8%), energy from charcoal represented 2126.6 MJ (2.44%), and energy from dung-cakes made up 157 MJ (0.18%). These figures demonstrate that traditional biomass fuels still constitute the largest energy supply of 85,278 MJ (97.8 %) out of the total 87,172 MJ energy consumed by a household per year.

The total energy consumed by a household from kerosene oil was estimated to be 1064 MJ/year (1.22%), grid-electricity 656.77 (0.75%), biogas 155.6 MJ (0.18%) and solar power 17.12 MJ (0.02%). This indicates that energy derived from modern, clean, and renewable sources (electricity, biogas, and solar combined) accounts for only 0.95% (830 MJ) of the total energy consumed by the household per year; while petroleum products accounted for 1.22% (1064 MJ).

Table 19. Mean total household energy consumption by energy source in megajoules

Fuel type	Consumption (MJ/day)	Consumption (MJ/month)	Per capita (MJ/year)	Consumption (MJ/year)	% share fuel	Sub-total (MJ)	% share source
Fuelwood	206.38	6277.25	12071.63	75327.00	86.41	85278	97.83
Agri. residue	21.01	638.95	1228.75	7667.42	8.80		
Charcoal	5.83	177.21	340.80	2126.57	2.44		
Dung cakes	0.43	13.09	25.17	157.05	0.18		
Kerosene	2.92	88.67	170.52	1064.05	1.22	1064	1.22
Electricity	1.80	54.73	105.25	656.77	0.75	830	0.95
Biogas	0.43	12.97	24.94	155.60	0.18		
Solar	0.05	1.43	2.74	17.12	0.02		
Total	239	7264	13970	87172			

Given that almost all the biomass energy consumed by rural households in Ethiopia is used for cooking and baking end-uses (Guta, 2012), it can be concluded from the results in Table 19 that at least 97% of the total household energy consumption in the study areas is used for cooking and baking. This means that substantive energy substitution and transition in rural Ethiopia is heavily contingent on the extent to which the energy demand for cooking and baking end-uses is addressed above and beyond the significant lighting energy substitution. Biomass is a renewable energy source. Yet, for the rate of consumption is far greater than the rate of sustainable harvest, household energy use from solid biomass as it stands now in rural Ethiopia is unsustainable.

According to the Ethiopian energy balance statistics, solid biomass fuels accounted for 98.7% of the total household energy supply while electricity and petroleum combined constituted 1.3% for the period between 2006 and 2010 at the national level (MoWIE, 2013). In 2012, fuelwood accounted for 90.9% of the total rural household energy use for cooking and baking, agri residue 8%, and charcoal 0.2% at the national level (Mondal et al., 2018). Comparing these values with our findings suggests that the rural household sector in Ethiopia is still heavily reliant on solid biomass fuels for domestic energy use and there is little sign that this heavy reliance is declining any time soon.

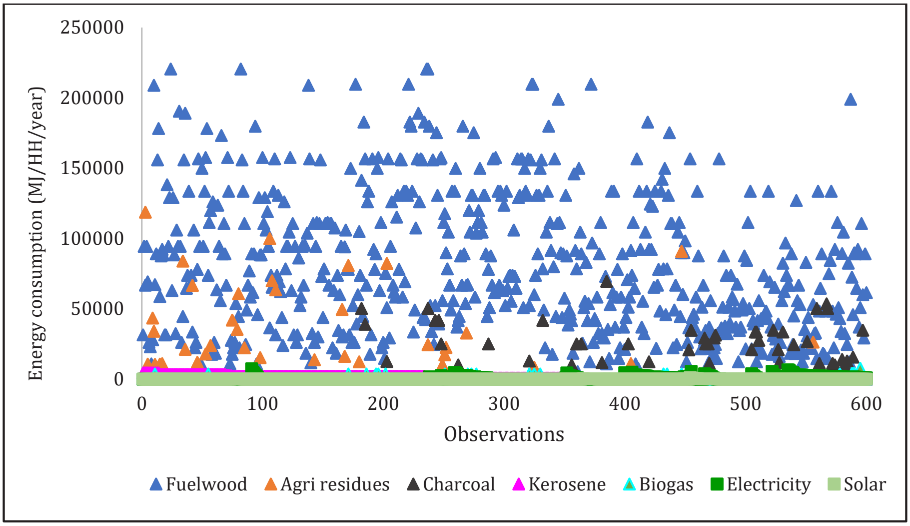

Figure 7. Scatter plot of household energy consumption (MJ/year) from the different fuels

On the bright side, rural household energy consumption for lighting is taking up modern and clean sources. According to Mondal et al. (2018), the share of energy from electricity in the total energy consumption of rural households in Ethiopia in 2012 was approx. 0.1%, biogas 0%, and solar power 0%. Compared to these values, our findings of energy from electricity constituting 0.75%, biogas 0.18%, and solar 0.02% in the total energy consumption of sample households indicates the existence of energy substitution and transition towards clean and modern lighting fuels in rural Ethiopia. However, as the descriptive analysis in section 3.2.3 illustrates, this energy transition is partial. As such, many households that are connected to the grid or that have adopted solar lighting still consume a considerable amount of kerosene and batteries as back-up and secondary lighting fuels. This could be due to the unreliability of electricity supply and frequent power outages, and the limited capacity of the solar PVs/lanterns.

4. Conclusions and policy implications

Heavy reliance on solid biomass fuels and petroleum products for domestic energy use has adverse effects on human health and productivity, deforestation, and environmental degradation in Ethiopia. This effectively undermines the sustainable development stride and climate change mitigation potential of the country. This study presents an empirical analysis of rural household energy sources, consumption patterns, and the contribution of modern and renewable sources in the total household energy consumption in rural southern Ethiopia in light of the recent energy development efforts in the country.

The findings revealed that the overwhelming majority (>97%) of the sample households depend on traditional solid biomass fuels (mainly fuelwood) as primary energy sources for cooking and baking end-uses, whereas the use of biogas and electricity for cooking is yet limited. In contrast, the study finds that the use of renewable, modern, and clean energy sources (electricity and solar PVs systems) for lighting is steadily picking up. The findings highlighted that the current household energy use in rural SNNPRS is massively dominated by woody biomass fuels particularly for cooking and baking end-uses (which constitute more than 97% of the total household energy use). As such, the study finds no evidence of significant energy substitution to suggest that this heavy dependence is slowing down. Conversely, the study finds that, despite its invisible share (≈ 1%), energy use from modern and renewable sources has led to significant energy substitution and (partial) transition from kerosene-based towards clean lighting fuels compared to the 'almost none' in the 2000s. This suggests that whilst Ethiopia's government efforts of modern energy supply over the last decade are improving the rural access to renewable and clean lighting fuels, they have had little impact in tackling the biggest problem of heavy dependence on woody biomass fuels for cooking and baking end-uses.

In terms of future energy policy directions, this evidence signifies the need to address some critical issues. First, the existing dissemination approach and utilization of biogas systems needs to be reassessed. Second, market supply of electrical-cooking and baking appliances to rural households at affordable prices (including government subsidies) should be considered to increase rural use of electricity for cooking and baking in light of Ethiopia's target to achieving electricity access for all. Thirdly, the rural electricity supply is currently unreliable and insufficient; and hence developing green mini-grids (mini-hydro) and off-grid renewable hybrid energy supply systems could be a viable option. Fourth, since woodfuels will likely remain the primary energy sources of rural households in Ethiopia for decades to come, Ethiopia needs to address the rural bio-energy demand for cooking and baking by developing alternative and more sustainable biomass energy sources and utilization strategies including promoting large-scale state and private forest developments for domestic energy, development of bio-energy from bio-wastes; promotion of energy-saving and affordable cooking and baking technologies alongside the current efforts of ensuring access to electricity for all.

5. References

Abdisa. L.T. (2018). Power outages, economic cost, and firm performance: Evidence from Ethiopia. Utilities Policy, 53(C):111-120.

Abebe, T. (2005). Diversity in homegarden agroforestry systems of Southern Ethiopia. PhD thesis, Wageningen University, Wageningen, The Netherlands. https://pdfs.semanticscholar.org/33f5/18ba8f43a3f1b6c571ab071c8ef607ae2f76.pdf (Accessed 12.02.19).

Asfaw, A., Demissie, Y. (2012). Sustainable Household Energy for Addis Ababa, Ethiopia. Consilience: Journal of Sustainable Develeopment, 8: 1-11.

Barfuss, I., Gwavuya, S., Abele, S., Müller, J. (2013). Biogas production vs. dung combustion as household energy in rural Ethiopia. Conference Paper presented at CIGR International Symposium on Sustainable Bioproduction - Water, Energy and Food. https://d-nb.info/1031708790/34 (Accessed 11.07.19).

Barnes, D.F., Golumbeanu, R., Diaw, I. (2016). Beyond Electricity Access: Output-Based Aid and Rural Electrification in Ethiopia. Energy for Development, Washington, DC. World Bank. http://documents.worldbank.org/curated/en/781791487789244953/pdf/112967-WP-P105651-PUBLIC-Beyond-Electricity-Access-Ethiopia-FINAL.pdf (Accessed 11.01.19).

Bekele, M., Berhanu, L. (2001). State of Forest Genetic Resources in Ethiopia. Sub-Regional Workshop on the Conservation, Management, Sustainable Utilization and Enhancement of Forest Genetic Resources in Sahelian and North-Sudanian Africa. http://www.fao.org/3/a-ab387e.pdf (Accessed 08.03.19).

Carlsson, F., Demeke, E., Martinsson, P., Tesemma, T. (2018). Cost of Power Outages for Manufacturing Firms in Ethiopia: A Stated Preference Study. Working Paper in Economics No. 731. University of Gothenburg, Sweden.

Cochran, W.G. (1977). Sampling Techniques, Wiley, New York.

CSA. (2013). Central Statistical Agency of Ethiopia. Population Projection for All Regions from 2014 – 2017. Addis Ababa. https://www.academia.edu/30252151/Federal_Democratic_Republic_of_Ethiopia_Central_Statistical_Agency_Population_Projection_of_Ethiopia_for_All_Regions_At_Wereda_Level_from_2014_2017 (Accessed 03.03.19).

CSA. (2012). Ethiopian Welfare Monitoring Survey Report of 2011; Central Statistical Agency (CSA) of Ethiopia. http://catalog.ihsn.org/index.php/catalog/3124 (Accessed 08.03.19).

Duguma, L. A., ..., Bernard, F. (2019). Deforestation and Forest Degradation as an Environmental Behaviour: Unpacking Realities Shaping Community Actions. Land, 8 (26).

EFAP. (1994). Ethiopian Forestry Action Program (EFAP): Final report Vol. II- The Challenges of Development: Ministry of Natural Resources Development and Environment Protection, Addis Ababa.

FAO. (2015). Global forest resources assessment 2015: Country report- Ethiopia. Food and Agricultural Organisation of the United Nations, Rome. http://www.fao.org/3/a-az209e.pdf (Accessed 12.07.19).

FDRE. (2016). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan II (GTP I): 2015/16 – 2019/20. National Planning Commission; Addis. https://www.greengrowthknowledge.org/sites/default/files/downloads/policy-database/ETHIOPIA%29%20Growth%20and%20Transformation%20Plan%20II%2C%20Vol%20I.%20%20%282015%2C16-2019%2C20%29.pdf (Accessed 27.04.19).

FDRE. (2011). Federal Democratic Republic of Ethiopia, Ethiopia's Climate-Resilient Green Economy Strategy (CRGE) Addis Ababa, Ethiopia. https://www.undp.org/content/dam/ethiopia/docs/Ethiopia%20CRGE.pdf (Accessed 04.01.19).

FDRE. (2010). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan I (GTP I): 2010/11 – 2014/15. Ministry of Finance and Economic Development. Addis Ababa, Ethiopia. https://www.undp.org/content/dam/unct/ethiopia/docs/GTP%20English%20Vol1%20(1).pdf (Accessed 27.04.19).

Foley, J. (2015). Fundamentals of energy use in water pumping. The Official Journal of Irrigation Australia, 31(1):8-9.

Gebreegziabher, Z., Mekonnen, A., Kassie, M., Köhlin, G. (2012). Urban energy transition and technology adoption: The case of Tigrai, northern Ethiopia. Energy Economics, 34 (2): 410-418.

Gebreegziabher, Z. (2007). Household Fuel Consumption and Resource Use in Rural-Urban Ethiopia. PhD Thesis Wageningen University, The Netherlands. https://library.wur.nl/WebQuery/wurpubs/fulltext/31629 (Accessed 01.02.19).

Gupta, G., Köhlin, G. (2006). Preferences in Urban Domestic Fuel Demand: The Case of Kolkata, India. Ecological Economics, 57(1): 107-121.

Guta, D.D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. Energy Policy, 75: 217-227.

Guta, D.D. (2012). Assessment of Biomass Fuel Resource Potential and Utilization in Ethiopia: Sourcing Strategies for Renewable Energies. Int journal of Renewable Energy Research, 2(1).

Guta, D. D. (2011). Energy Demand in Rural Ethiopia from a Household Perspective: A Panel Data Analysis. J of Energy and Development, 35 (2): 195-213.

Guta, F., Damte, A., Ferede, T. (2015). The Residential Demand for Electricity in Ethiopia. Environment for Development Initiative. https://www.jstor.org/stable/resrep15016?seq=1#page_scan_tab_contents (Accessed 12.03.19).

Gwavuya, S.G, Abele, S., Barfuss, I., Zeller, M., Müller, J. (2012). Household energy economics in rural Ethiopia: A cost-benefit analysis of biogas energy. Renewable Energy, 48: 202-209.

Hall, D. O., Rosillo-Calle, F., Woods, J. (1994). Biomass utilization in households and industry—Energy use and development. Chemosphere, 29: 1099–1119.

IEA. (2019). Atlas of Energy: Electricity consumption per capita in 2016 Ethiopia, International Energy Agency. http://energyatlas.iea.org/#!/tellmap/-1118783123/1 (Accessed 24.03.19).

IEA. (2018). Energy statistics Ethiopia 1990 – 2016. International Energy Agency. https://www.iea.org/statistics/?country=ETHIOPIA&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES (Accessed 28.06.19).

IEA. (2014). Defining energy access. International Energy Agency. https://www.iea.org/energyaccess/methodology/ (Accessed 19.06.19)

IEA. (2012). Pico Solar PV systems for Remote Homes. Photovoltaic Solar Systems programme. International Energy Agency. http://www.iea-pvps.org/fileadmin/dam/public/report/technical/rep9_12_PVPS_Pico_Solar_PV_Systems_apr13.pdf (Accessed 01.01.19).

IRENA. (2016). Measuring small-scale biogas capacity and production. International Renewable Energy Agency IRENA, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Statistics_Measuring_small-scale_biogas_2016.pdf (Accessed 03.03.19).

Kebede, B., Bekele, A., Kedir, E. (2002). Can the urban poor afford modern energy? The case of Ethiopia. Energy Policy, 30 (11–12): 1029-1045.

Kebede, D., Kiflu, A. (2014). Design of Biogas Stove for Injera Baking Application. Int J of Novel Research in Engineering and Science, 1(1); 6-21.

Khan, B., Singh, P. (2017). The Current and Future States of Ethiopia's Energy Sector and Potential for Green Energy: A Comprehensive Study. Int Journal of Engineering Research in Africa, 33:115-139.

Lemma, M. (2014). Power Africa Geothermal Roadshow: Ethiopian Electric Power Strategy and Investment Division, The Ethiopian Electric Power (EEP). https://geothermal.org/Annual_Meeting/PDFs/Mekuria%20Lemma%20Geothermal.pdf (Accessed 05.01.19).

MEFCC. (2017). Federal Democratic Republic of Ethiopia; Ministry of Environment, Forest and Climate Change. Proposal for REDD+ investment in Ethiopia. http://www.mofed.gov.et/documents/10182/32227/REDD%2B+Investment++Plan_program+document.pdf/c39b22eb-abfc-48be-907c-b44ff4505e55(Accessed 03. 02. 18).

Mekonnen, A., Köhlin, G. (2009). Determinants of Household Fuel Choice in Major Cities in Ethiopia. Working papers in economics No 399 University of Gothenburg, Sweden. https://gupea.ub.gu.se/bitstream/2077/21490/1/gupea_2077_21490_1.pdf (Accessed 26.06.19.

Mekonnen, A. (1999). Rural household biomass fuel production and consumption in Ethiopia: a case study. Journal of Forest Economics, 1(41).

Mondal, A.H., Bryan, E., Ringler, C., Mekonnen, D., Rosegrant, M. (2018). Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. Energy, 149:161-172.

MoWE. (2012). Federal Democratic Republic of Ethiopia: Ministry of Water and Energy Scaling - Up Renewable Energy Program Ethiopia. Addis Ababa, Ethiopia. https://www.oecd.org/env/cc/TADELE_FDRE%20Ethiopia%20Scaling%20-%20Up%20Renewable%20Energy%20Program%202012.pdf (Accessed 17.02.19)

MoWIE. (2013). Updated Rapid Assessment Gap Analysis on Sustainable Energy for All (SEforALL). Ministry of Water Irrigation and Electricity (MoWIE), Ethiopia. https://www.se4all-frica.org/fileadmin/uploads/se4all/Documents/Country_RAGAs/MWH_-_Updated-Rapid_Gap_Analysis.pdf (Accessed 12.01.19).

Müggenburg, H., Tillmans, A., Schweizer-Ries, P., Raabe, T., Adelmann, P. (2012). Social acceptance of PicoPV systems as a means of rural electrification — A socio-technical case study in Ethiopia. Energy for Sustain. Develop.,16(1).

Mulugeta, B., Demissie, S.W., Nega, D.T. (2017). Design, Optimization and CFD Simulation of Improved Biogas Burner for ‘Injera’ Baking in Ethiopia. Int Journal of Engineering Research & Technology, 6(1).

Mulugetta, Y. (1999). Energy in Rural Ethiopia: Consumption Patterns, Associated Problems, and Prospects for a Sustainable Energy Strategy. Energy Sources, 21: 527–539.

Negash, D., Abegaz, A., Smith, J.U., Araya, H., Gelana, B. (2017). Household energy and recycling of nutrients and carbon to the soil in integrated crop-livestock farming systems: a case study in Kumbursa village, Central Highlands of Ethiopia. Bioenergy, 9(10).

Nelson, V.C., Starcher, K. L. (2015). Introduction to Renewable Energy 2nd Ed. CRC Press.

Padam, G., ..., Gina, F. (2018). Ethiopia – Beyond Connections: Energy Access Diagnostic Report Based on the Multi-Tier Framework. The World Bank. https://openknowledge.worldbank.org/handle/10986/30102 (Accessed 17.04.19)

Power Africa. (2018). Power Africa Fact Sheet Ethiopia/ Success Story. https://Www.Usaid.Gov/Powerafrica/Ethiopia (Accessed 11.02.19).

Quaschning, V.V. (2019). Renewable Energy and Climate Change, 2nd Edi., Wiley.

SE4ALL. (2017). Access to electricity, rural (% of rural population) Ethiopia, 2017. Sustainable Energy for All. https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS (Accessed 21.03.19).

Shanko, M., Lakew, H. (2011). Household Energy Baseline Survey in SNNPR: Final Report. GIZ: Eco – Bio-Energy Department. https://energypedia.info/images/3/3b/Household_Bio-Energy_Baseline_Survey_in_SNNP_Region-Ethiopia.pdf (Accessed 21.12.18).

Smith, K., ..., Khalil, M. (2000). Greenhouse Gases from Small-scale combustion Devices in Developing countries, Phase IIA: Household stoves in India. United States Environmental Protection Agency, Report No EPA/600/R-00/052.

SNV. (2019). The Africa biogas partnership program (ABPP), SNV Ethiopia. https://www.africabiogas.org/countries/ethiopia/ (Accessed 10.03.19)

SNV. (2008). National Biogas Programme Ethiopia: Programme Implementation Document. Netherlands Development Organization SNV/Ethiopia. http://www.bibalex.org/search4dev/files/338816/172299.pdf (Accessed 08.01.19).

Tilahun, F. T., Bhandari, R., Mamo, M. (2017). Economically realizable solar process heat solutions in Ethiopian textile industry with demand derived from artificial neural network data. WSEAS Transactions on Power Systems,12.

Tucho, G. T. (2016). Improving the energy system for a rural community in developing countries: Challenges and sustainable opportunities in using renewable energy resources in Ethiopia. University of Groningen. https://www.rug.nl/research/portal/files/38569020/Chapter_2_.pdf (Accessed 17.03.19).

Tucho, G.T., Nonhebel, S. (2015). Bio-wastes as an alternative household cooking energy source in Ethiopia. Energies, 8: 9565–9583.

Tucho, G.T., Weesie, P.D.M., Nonhebel, S. (2014). Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. Renew and Sustain Energy Reviews, 40: 422–431.

Wassie, Y.T., Adaramola, M.S. (2019). Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. Renew. Sustain. Energy Reviews, 111: 377-391.

World Bank. (2018a). Population Total- Ethiopia 2018. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=SL-ET (Accessed 29.06.19).

World Bank. (2018b). Energy use per capita: Ethiopia in 2014: The World Bank. https://www.google.com/search?q=per+capita+energy+consumption+ethiopia&ie=&oe= (Accessed 19.02.19).

World Bank. (2015). World development indicators 2015 (English). Washington DC. http://documents.worldbank.org/curated/en/795941468338533334/World-development-indicators-2015 (Accessed 01.03.19).

Yurnaidi, Z., Kim, S. (2018). Reducing Biomass Utilization in the Ethiopia Energy System: A National Modelling Analysis. Energies*, 11(7):* 1745.

Zeleke, B., Getachew, M. (2017). Traditional Cattle Husbandry Practice in Gamo Gofa Zone, Southern Western Ethiopia. Int. Journal of Novel Research in Life Sciences, 4(5): 1-7.

Appendix I: Summary table of daily biogas production and use estimation in the study areas

Table 1. Estimation of biogas consumption for cooking and heating

Measurements (computations)	Results	Data sources
Average digester capacity of the biogas plants studied	$6m^3$	Own field study
Average daily biogas production capacity of a $6m^3$ fixed dome digester in developing countries	1.6 – 2.4 m^3/day	Eshete et al. [2006] Schwarz [2007]
Quantity of cow-dung needed to produce the average daily biogas requirement (1.6 -2.4 m^3) per day	40 – 60 kg/day	Eshete et al. [2006] Schwarz [2007]
Average quantity of cow-dung currently fed to the digesters/day in kg (measured in the study areas)	22. 50 kg/day	Own measurement (2018)
Average biogas-based cooking hours/day per HH	1.05 hrs/day	Own data (2018)
Gas consumption rate of typical (small-sized) biogas burner (stove) in Ethiopia from previous tests	0.475 m^3/hr	Khandelwal and Gupta [2009]
Estimated biogas consumption for cooking/day	= 1.05 hrs * 0.475 m^3/hr = 0.50 m^3/day	
Estimated biogas consumption for cooking/year	= 0.50 m^3/day * 365 ≈ 182 m^3/year	
Fuelwood equivalent of biogas consumed for cooking per year ($1m^3$ biogas ≈ 3.47 kg of fuelwood) [Yimer et al., 2014]	= (182 m^3) * 3.47 kg/m^3 = 631.7 kg	

Table 2. Estimation of daily biogas consumption for lighting and total biogas use per day

Estimated average biogas-lighting hours/HH/ day	2.30 hrs	Own survey (2018)
Biogas lamps gas consumption rate in m^3/hr	0.048 m^3/hr	Khandelwal and Gupta [2009]
Estimated biogas consumed for lighting/HH/day	= 2.30 hrs * 0.048 m^3/hr = 0.110 m^3/day	
Estimated biogas consumed for lighting/HH/year	= 0.110 m^3/day * 365 = 40.15 m^3/year	
Kerosene equivalent of biogas consumed for lighting per year (1 m^3 biogas ≈ 0.62L of kerosene) [Yimer et al., 2014]	= (40.15 m^3) * 0.62 L/m^3 = 25. 0 L	
Total biogas consumption/HH/day	= 0.50 m^3 + 0.11 m^3 = 0.61 m^3/day	
Total biogas consumption/HH/year	= 0.61m^3 * 365 = 222.65 m^3/year	
Estimated current production efficiency of the biogas plants compared to their production capacity	= 25 - 38%	

Paper VI

Determinants of household energy choices in rural sub-Saharan Africa: An example from southern Ethiopia

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Abstract

This study investigates the major factors influencing rural household energy choices for cooking and lighting in southern Ethiopia using data from a cross-sectional survey of 605 households and direct observational studies. Chi-square tests and Multivariate Probit (MVP) model were used to analyse the data. The findings showed that most of the rural households depend on fuelwood (90.70%) while only 3.14% use clean fuels as the main energy sources for cooking. In contrast, 50% use kerosene, 29% electricity, 19% solar, and 1.98% biogas as primary lighting energy sources. The Chi-square tests revealed that a statistically significant relationship exists between household cooking fuel choices and distance to wood source, household size, income level, and location. Empirical results of the MVP model indicated that household's choice of energy for lighting is significantly influenced by income level, family size, access to road, location, education, and distance to markets. Wealthier and more educated households residing near road access were more likely to use clean lighting energy sources. By contrast, poorer households residing in areas with limited road access use kerosene and dry-cell batteries. However, higher-income level and grid-connection have not led households to completely abandon the use of traditional cooking and lighting fuels. While income remains a principal factor, the study showed that various non-income factors also play a major role in determining rural household's energy choices and energy transition. And hence, policymakers and energy planners in Ethiopia and sub-Saharan Africa at large need to take into account these diverse factors when designing energy policies and interventions to rural areas.

Keywords: *Rural households, cooking fuel choice, lighting fuel choice, energy-stacking*

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1. Introduction

It is estimated that about 2.5 billion people worldwide depend on traditional biomass fuels to meet their basic cooking energy requirements; and more than one billion people do not have access to electricity (IEA, 2018a). In sub-Saharan Africa, about 600 million people (over half of the population) have no access to electricity, and 890 million people still cook with traditional biomass fuels (IEA, 2018a). In the context of Ethiopia, more than 91% of the total final energy consumed in the country is derived from biomass fuels (IEA, 2018b); and over 90% of the population depends on traditional solid biomass fuels (fuelwood, charcoal, crop-residues, and dung-cakes) for cooking (Guta, 2012; Lemenih and Bongers, 2011). The reliance on solid biomass fuels and kerosene as primary energy sources for cooking and lighting respectively is extreme in rural and off-grid areas of Ethiopia where approx. 80% of the population lives (Tucho et al., 2016).

Against this backdrop, the government of Ethiopia has been making considerable efforts in recent years to increase the rural access and use of modern and clean energy sources, thereby mitigate the negative socio-economic, environmental, and health impacts of the heavy reliance on traditional fuels (FDRE, 2010). As a result, rural electricity coverage in Ethiopia has increased from 6% in 2010 to 31% in 2016 (World Bank, 2017). Reports from the government of Ethiopia also indicate that the dissemination and use of solar photovoltaic (PV) systems, domestic biogas plants, and improved biomass cookstoves is steadily increasing in recent years (FDRE, 2016).

In light of these signs of progress, however, an important question of what determines the household energy choices in rural Ethiopia remains unaddressed. Most empirical studies on household energy choices and energy transition process in Ethiopia to date have focused on urban households albeit the majority of the population living in rural areas (e.g. Alem et al., 2016; Gebreegziabher et., 2012; Kebede et al., 2002; Mekonnen and Köhlin, 2009). Understanding the rural households' energy choice behaviours and the underlying determinants and drivers is, therefore, of paramount importance for the Ethiopian energy sector to design relevant policy interventions that promote the use of modern and cleaner energy sources in rural areas.

Two major strands of theories are often employed by researchers to explain household energy choices and energy transition process: the “energy ladder” and “energy stacking” (Campbell et al., 2003; Heltberg et al., 2004). The energy ladder (fuel-switching) model proposes that faced with a range of energy use options, households switch from one type of fuel to another when their income level increases (Hosier and Dowd, 1987). Climbing up the energy ladder from the bottom to top, the model ranks household energy sources into three levels: 1) Primitive- comprising mainly of fuelwood, crop residues, and dung cakes; 2) Transitional – consisting of charcoal, kerosene, and coal; and 3) Advanced or modern - electricity, liquefied petroleum gas (LPG), biogas and other biofuels (Hosier and Dowd, 1987; Schlag and Zuzarte, 2008). The central idea behind the energy ladder model is that household energy choices are primarily determined by income levels, as such households undergo linear fuel switching as their income level increases.

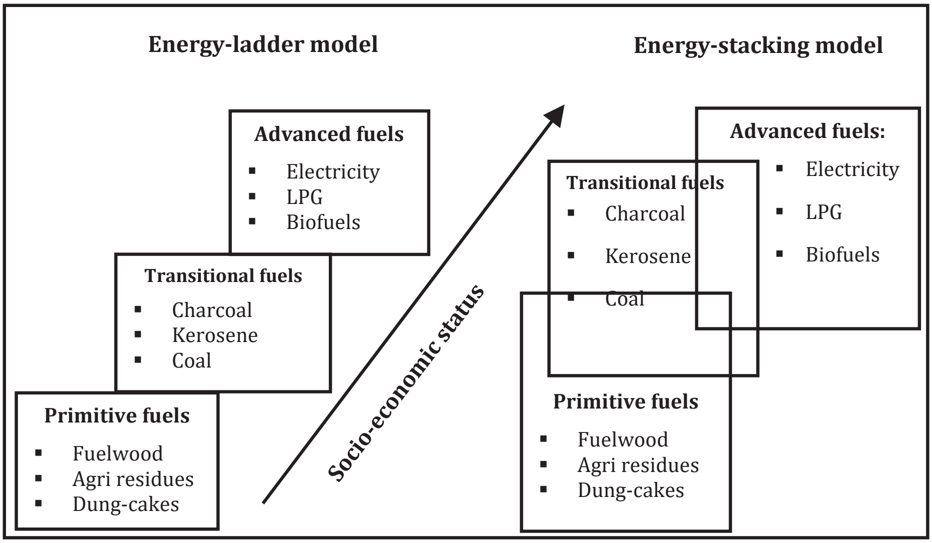

Figure 1. The energy transition process (based on Schlag and Zuzarte, 2008)

In contrast, the energy-stacking model argues that household energy choice behaviours and transition process, particularly in the developing world, does not necessarily follow a unidirectional simple switching from one energy source to another as depicted by the energy ladder model. This model contends that instead of completely leapfrogging from traditional fuels to modern ones, households would diversify their energy portfolio and use ‘multiple fuels’ irrespective of increase in their income levels (Masera et al., 2000).

The main rationale for the ‘multiple fuels use’ strategy of households is to maximum their energy utility and exploit complementarities between traditional and modern fuels (Kebede et al., 2002; Nansairo et al., 2011; Narain et al., 2008). According to the energy-stacking model, household energy transition is an incremental process resulting from complex interactions between economic, technological, institutional and socio-cultural factors and capabilities instead of a purely income-based unidirectional fuel-switching (Masera et al., 2000; Murphy, 2001). Empirical evidence also indicates that households’ energy choice decisions are influenced by several factors including income, availability of fuel, access to electricity, awareness and education level, household size, and many other factors (Campbell et al. 2003; Heltberg 2005; Nansairo et al., 2011).

In light of the theoretical models mentioned-above and the recent signs of progress in modern energy access in Ethiopia, this study seeks to explore the factors determining rural households’ energy choices for cooking and lighting from a cross-sectional survey in the southern region. In particular, the study aims to shed light on key factors affecting the rural households’ choice of modern and renewable energy vis-a-vis traditional fuels. Thereby contributing to the scientific knowledge and policy-making for the household energy transition in the context of rural Ethiopia and Sub-Saharan Africa at large.

2. Materials and Methods

2.1. Study areas and sampling

This study was undertaken in four randomly selected rural districts of the Southern Nations Nationalities and Peoples Regional State (SNNPRS) of Ethiopia. These districts were: Aleta-wondo, Boloso-sore, Cheha and Mirab-abaya (Figure 2). Geographically, the SNNPRS lies between Latitudes 4°43’- 8°58’ North and Longitudes 34°88’- 39°14’ East. Administratively, the region is divided into 14 zones and 4 special *woredas* (districts), comprising of a total of 137 rural districts (*woredas*) and 22 urban administrations (CSA, 2013). The *woredas* are further sub-divided into *kebeles*, the smallest administrative units of Ethiopia. The total population of the SNNPRS was estimated to be 19. 2 million in 2017; of which approx. 90% were rural inhabitants in 3,709 *kebeles* and about 10 % were urban residents in 324 *kebeles* (CSA, 2013).

A multi-stage stratified random sampling approach was used to select sample districts and households for the study. In the first stage, 23 of the total 137 rural districts in the region, where the deployment of renewable energy technologies has been taking place since 2008 were identified based on data from the Regional Mines and Energy Agency. This was needed for the study to represent households that have access to renewable and clean energy sources and technologies. The 23 districts were then clustered into three agro-climatic zones as highland, midland and lowland to capture potential effects of agro-climatic related factors on household energy choices.

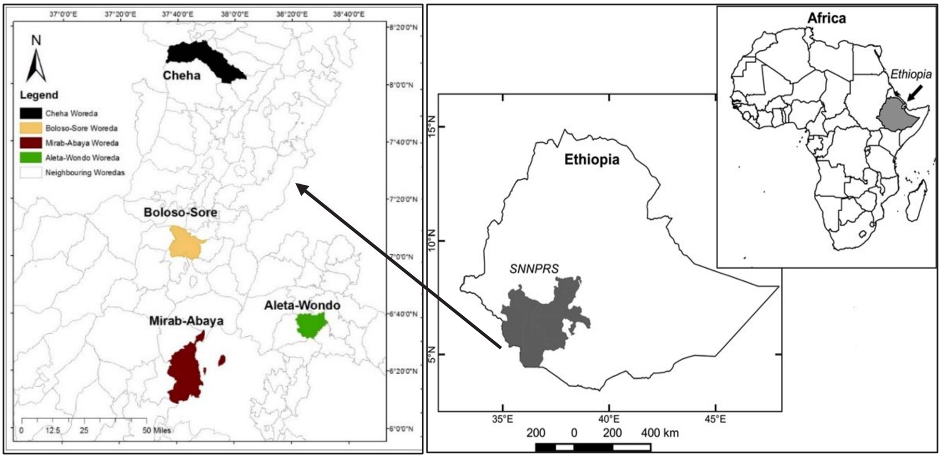

Figure 2. Location map of the SNNPRS region and the study districts (*woredas*)

Subsequently, two districts from the highland group, one from the midland and one from the lowland were selected randomly. Two sample districts were selected from the highland category because more than half of the 23 rural districts identified fell in this category. Accordingly, Aleta-wondo and Cheha districts were selected from the highland category; whereas Boloso-sore and Mirab-abaya were selected from the midland and lowland categories, respectively.

The total population of Aleta-wondo district in 2017 was estimated to be 187,957 consisting of 33, 738 households and that of Cheha district was estimated to be 122,770 composed of 24,554 households. The total population of Boloso-sore in 2017 was estimated to be 187,558 made up of 36,410 households and that of Mirab-abaya district was 90, 508 composed of 12,784 households (CSA, 2013).

In the second stage, a representative sample size for the study was estimated at 95% confidence level, 4% precision level (for large sample size and smaller allowable error between the sample estimates and true population values) and p = 0.5 (for unknown population proportion to generate the largest sample size) following Cochran (1977).

$$N = \frac{(z^2 \boldsymbol{\alpha}/_2)\ (p)(1-p)}{e^2} \qquad (1)$$

$$N = \frac{(3.8416)\ .\ (0.5)(0.5)}{0.04^2} \quad = \quad 600$$

Where:

N= is the desired sample size
P = 0.5 is the assumed population proportion expected to have access to renewables
e= 0.04 is the desired precision (or margin of error) at 4%
$Z_{\alpha/2}$ = 1.96 is the critical value for a two-tailed hypothesis test at 5% significance level

Allowing for a non-response rate of 10%, the total sample size was calculated at 660. This total sample size was then distributed to the four sample districts by using the probability proportional to the household size (PHS) method. Hence, of the total 660 sample households calculated, 207 were allotted to Aleta-wondo district, 224 to Boloso-sore, 151 to Cheha and 78 to Mirab-abaya districts. In the third stage, three *Kebeles* were randomly chosen in each sample district and the sample size allotted to each district was distributed to the three *kebeles* using the same PHS method. Finally, a random selection of individual sample households was made from a complete list of all households in each *Kebele* by using a lottery method for the detailed study.

2.2. Data sources and collection methods

2.2.1. Household surveys:

A cross-sectional survey of sample households was carried out by using semi-structured questionnaires, which were administered through a face-to-face interview. To ensure that the survey instruments and data collected are reliable and representative, several considerations were made in the designing of the questionnaires. The most important considerations included identifying the characteristics of the target populations and ensuring that questions are designed to generate the desired outcome and represent the diverse socio-economic classes in the population. Other considerations included the use of multiple (cross-validating) questions, use of local language, and balancing of open and close-ended questions. To this end, preliminary studies were conducted in each sample district prior to designing the questionnaires, and information was gathered on various variables of the research. This was followed by a systematic development of the survey questionnaire and pretesting on 24 randomly selected households. The results from the pre-test were used to improve and refine the survey instruments. The actual survey was finally carried out between January and December of 2018 in such a way that sample households in each district were randomly assigned to the four seasons in Ethiopia to contain potential effects of seasonality on household energy choices.

2.2.2. Direct observational studies and key informant interviews

To better understand the energy choices of the rural households under normal settings and reduce potential bias from self-reported survey data, direct observational studies of actual cooking practices and fuel choices, and lighting energy uses of 48 households from within the total samples was carried out for a total of two weeks. The data gathered from the direct observational studies were later used to cross-validate the responses from the survey and substantiate findings from the empirical analysis. In addition, key informant interviews were conducted with a total of 20 informants selected on the basis of their knowledge and experience in rural household energy supply and fuel choices. The key informants included male and female household-heads, local alternative energy and technologies experts, promoters, and researchers.

2.3. Data analysis and interpretation

2.3.1. Descriptive and inferential statistics

A combination of parametric and non-parametric methods was used to analyse the data collected. Since the distribution of sample households in each type of primary cooking fuel was unequal and disproportionately skewed towards fuelwood (see Table 3), the assumptions of traditional parametric statistical methods (normal distribution of data, homogeneity of variance) could not be met. Hence, conventional parametric estimations will be biased and could lead to distorted and inaccurate estimates (McHugh, 2013).

Moreover, the Chi-square (χ^2) test for independence of households' choices of cooking fuels indicated a statistically insignificant relationship ($\chi^2 = 20.96$, $p = 0.051$), suggesting that the decision making of a household to use one cooking fuel type is not significantly correlated with the other. This is contrary to the findings of other studies (e.g. Behera et al., 2015; Rahut et al., 2019) which showed a significant correlation between household cooking fuel choices. Accordingly, the Pearson's Chi-square (χ^2) test (a nonparametric test for unrelated dichotomous outcome variables) was used to determine whether a relationship exists between household cooking fuel choices and important explanatory variables (demographic, economic, non-economic) following McHugh (2013).

2.3.2. Econometric analysis: The Multivariate Probit (MVP) Model

Analysis of household energy sources for lighting showed that many of the households use multiple sources of energy. The primary sources of energy for lighting are kerosene, electricity, solar, and to a lesser extent biogas. However, households also utilize dry-cell batteries and candles as back-up and secondary lighting energy sources. In many cases, these lighting energy sources are used simultaneously as complements (hence are not mutually exclusive) while in other cases they are used as substitutes. Unlike the case of cooking fuel choices, the χ^2 test of independence showed that the households' lighting energy choices are correlated with each other ($p < 0.0001$).

The appropriate econometric model to analyse correlated multivariate binary outcomes is hence the Multivariate Probit model (MVP) (Edwards and Allenby, 2003; Golob and Regan, 2002). Unlike single-equation probit/logit and multinomial probit/logit models, MVP models allow the joint prediction of multivariate interdependent binary outcomes (the choice decision of one type of lighting fuel is correlated with another type of fuel) against a set of explanatory variables (Golob and Regan, 2002). Given a set of energy choice options, the MVP model estimates the influence of explanatory variables on the probability of choice of each of the energy options jointly, while allowing the error term to be correlated. To this end, five most commonly used lighting energy sources (primary and secondary) were identified and set as dependent variables (energy choice options): 1) kerosene, 2) electricity, 3) solar, 4) biogas, and 5) batteries.

For each lighting energy option, the household is faced with a binary choice (1= usage of the particular lighting fuel, or 0= otherwise).

Following the works of Ali et al. (2019) and Behera et al. (2015), the MVP model used to analyse the factors determining lighting energy choice decisions of rural households in this study, with five dependent variables, $y_1, \ldots, y_5$ was formulated as:

$$y_i = 1 \quad \text{if} \quad \beta_i X' + \varepsilon_i \; > \; 0 \qquad (2)$$

and

$$y_i = 0 \quad \text{if} \quad \beta_i X' + \varepsilon_i \; \leq \; 0, \quad i \; = \; 1,2,\ldots 5$$

where X is a vector of the explanatory variables; β_1, β_2, β_3, β_4 and β_5 are conformable parameter vectors and ε_1, ε_2, ε_3, ε_4 and ε_5 are random errors distributed as a multivariate normal distribution with zero mean and unitary variance.

Table 1. Explanatory variables selected for the multivariate model

Variable (X_i)	Unit (definition)	Expected relation
Gender of HH head (dummy variable)	1 = female, 0= otherwise	+
Age	Age of the household head in years	−
Education level	Number of years of schooling of the HH head	+
Total household size	Total number of family members	±
Children in school	Number of family members enrolled in school	+
Gross annual income	Gross annual income of the HH in Eth. Birr (ETB)	+
Landholding size	Total landholding of the household in hectares	+
Cattle heads size	Total number of cattle heads of the household	+
Distance to market	Walking distance to local market (round-trip) in minutes	±
Distance to road	Walking distance to the road (round-trip) in minutes	±
Access to credit	1 = if the household has access to a credit facility, 0= otherwise	+
Location/district (dummies)	Setting Aleta-wondo as reference category D1 =1 if household lives in Boloso-sore, D1 = 0 otherwise; D2 =1 if household lives in Cheha, D2 = 0 otherwise D3 =1 if household lives in Mirab-abay, D3 = 0 otherwise	±

3. Results and discussions

3.1. Characteristics of sample households

Of the total 660 sample households determined for the study, 605 completed the survey. Data from the remaining 55 were either incomplete or highly inaccurate when cross-validated and hence excluded. The overall response rate was thus 91.70%. As shown in the summary statistics in Table 2, of the total 605 households surveyed, 31% were from Aleta-wondo, 34% from Boloso-sore, 22% from Cheha, and 13% were from Mirab-abaya district. In terms of gender, 84.13% of the sampled households were male-headed while the remaining 15.87% were headed by females. The average age of the household-heads was 48.30 years, and the average educational status of the household -heads, measured in terms of the total number of years of schooling completed, was 4.73. The average total household size was 6.24 persons, and the average landholding size per household was 0.7 hectares (ha). The average cattle holding per household was 3.50.

Table 2. Descriptive statistics of household characteristics and variables

Variables		Stat.	Total samples (N = 605)	SE
Location/district	Aleta-wondo	Freq (%).	189 (31%)	
	Boloso-sore	Freq (%).	204 (34%)	
	Cheha	Freq (%).	134 (22%)	
	Mirab-abaya	Freq (%).	78 (13%)	
Gender of HH head	Male	Freq (%).	509	
	Female	Freq (%).	96	
Age of HH Head		Mean	48.30	10.92
Education		Mean	4.73	3.77
Total household size		Mean	6.24	2.38
Family members enrolled in school		Mean	2.62	1.80
Total landholding in hectare (ha)		Mean	0.70	0.64
Number of cattle heads		Mean	3.50	2.36
Gross annual cash income in Eth. Birr		Mean	22, 155	22,350
Households with access to credit service		Freq (%).	212 (35%)	
Households connected to the grid		Freq (%).	194 (32 %)	
Households with improved cookstoves		Freq (%).	133 (22%)	
Households with Solar PV/lanterns		Freq (%).	137 (22.6%)	
Households with biogas plants installed		Freq (%).	32 (5.3%)	
Distance to wood source (round-trip), min.		Mean	62.40	75.20
Distance to market (round-trip), min.		Mean	105.20	35.20

Source: Own field survey, 2018.

The average gross annual cash income per household is 22,155 Eth. Birr (ETB) roughly $815 (in August 2018) but varies markedly between the highest in Mirab-abaya (ETB 38,123) and Aleta-wondo (ETB 28,358) districts to the lowest in Cheha (ETB 17,184) and Boloso-sore (ETB 16, 579). The reason is that many households in the former two districts are cash-crops growers while households in the latter are mostly food crop producers. With regard to occupation, households are generally engaged in multiple occupations. That being the case, 32% stated cash-crops growing (coffee, khat (*C. edulis*) and banana), 26% stated food crops production mainly '*Enset*'- Ethiopian false banana (*E. ventricosum*), cereals and root-crops whereas 24% are engaged in crop and livestock mixed-farming. In contrast, 13% earn their living from off-farm activities including daily labour and collection of forest products and 5 % pursue small-scale private business.

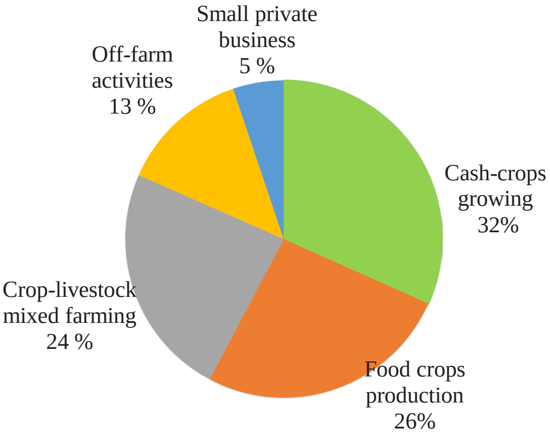

Figure 3. Distribution of sample households by primary occupations (source of income)

About 35% of the households have access to credit financing and 32% are connected to the grid. However, there was a large disparity in grid connection between households in the four districts. About 75% of the households in Mirab-abaya district are connected to the grid while only 8.8% of the households in Boloso-sore have a grid connection. About 22.6% of the sampled households own a solar home system (SHS) or PicoPV, and 22% own at least one improved cookstoves (ICS). By contrast, only 5.3% of the households had installed biogas plants. The average walking distance between households' home and the common wood source (forest or woodland) was 62.4 minutes (round-trip), and the average walking distance (round-trip) to the local market was 105.2 minutes.

3.2. Primary energy sources of households

3.2.1. Primary energy sources of households for cooking

Generally, the cooking fuel portfolio of sample households is dominated by traditional solid biomass fuels and the majority (90.7%) use fuelwood as the primary cooking fuel (see Table 3). This is followed by agri (crop) residues (3.14%), and charcoal (2.31%). In contrast, 3.14% of the sampled households use modern and clean fuels (electricity and biogas) as their primary energy source for cooking. On the other hand, the use of animal dung-cakes and kerosene oil for cooking is generally negligible.

Table 3: Primary cooking fuel used by households

Cooking fuel types	Frequency (N = 605)	Percent
Fuelwood	549	90.74
Agri residues	19	3.14
Charcoal	14	2.31
Electricity/biogas	19	3.14
Dung cakes and kerosene	4	0.67
Total	605	100

Source: Field survey 2018

These figures show that, in spite of the recent improvements in rural electricity coverage (32% compared to 6.6% in 2010 (World Bank, 2017)), the use of electricity for cooking is yet very limited. Likewise, out of the 5.3% biogas owners identified during the survey, only 1.98% use biogas as primary cooking fuel. This is because some of the biogas plants constructed in the study areas have malfunctioned. In those plants that are functional, the biogas produced is insufficient to meet the daily energy needs of the households for cooking and lighting. Although these fuels are identified as primary energy sources for cooking, it was found that about 36% of the households use multiple fuels for cooking as shown in Figure 4; whereas 64% solely depend on one type of cooking fuel, of which fuelwood is dominant. The results confirm that most of the rural households depend on fuelwood as the main cooking fuel. This substantiates the findings of previous studies in Ethiopia (e.g. Guta 2014; Mondal et al, 2018; Tucho, 2016). However, fuelwood is also used in combination with other fuels for complementarities. This, in part, concurs with the fuel-stacking (multiple fuel use) model of energy transition (Masera et al., 2000).

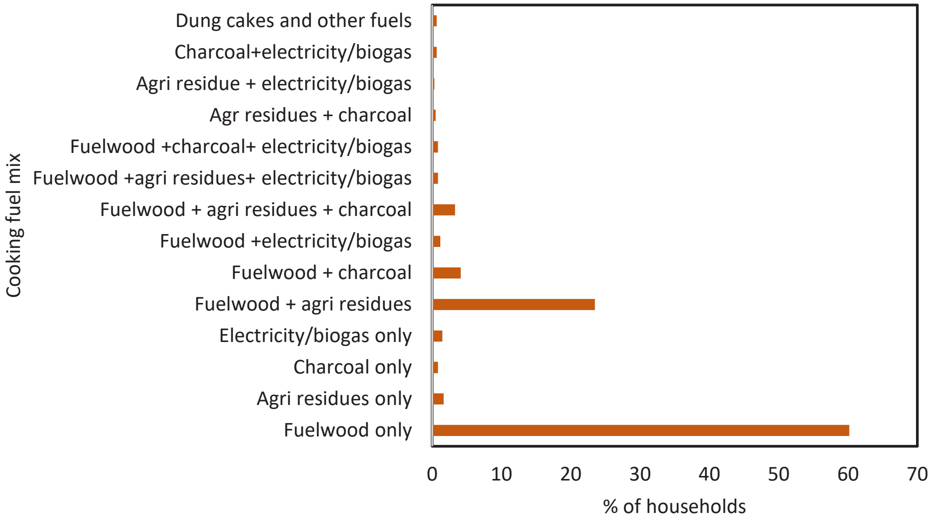

Figure 4. Proportion of sample households by coking fuel mix

3.2.2. Primary energy sources of households for lighting

Analysis of the primary energy sources of households for lighting (see Table 4) indicated that 50% of the households surveyed still depend on kerosene and traditional kerosene wick lamps, 28.93% use electricity, 19% solar power, and 1.98% biogas. Compared with the 70-80% dependency of rural households in the SNNPRS region on kerosene-based lighting in 2010 (MoWE, 2012), the present results indicate the existence of significant energy substitution and (partial) transition from kerosene towards clean and modern lighting energy use following the recent improvements in rural access to electricity and dissemination of solar and biogas technologies as evidenced in Table 4.

Table 4: Primary lighting energy sources used by households

Lighting energy sources	Frequency (N = 605)	Percent
Kerosene	303	50.08
Electricity	175	28.93
Solar PVs/lanterns	115	19.01
Biogas	12	1.98
Total	605	100

Source: Field survey 2018

However, a closer examination of the data (Figure 5) reveals that many of the sample households use multiple fuels for lighting. Evidently, out of the total sample households, 15.4% (mostly non-electrified) use a combination of kerosene and dry-cell batteries for lighting. About 12.9% (mostly grid-electrified) use a mix of grid electricity and kerosene. Similarly, 6.9% (mostly solar-electrified) combine solar power with kerosene; and 4.3% use a mix of solar power and batteries for lighting. Other lighting fuel mixes found were electricity and candles (2.3%), solar and candles (1.2%), and biogas and electricity (1%). This means that the proportion of sample households that solely depend on one type of lighting energy source (among the primary lighting energy sources shown in Table 4) is 55%; while the remaining 45% use multiple lighting energy sources.

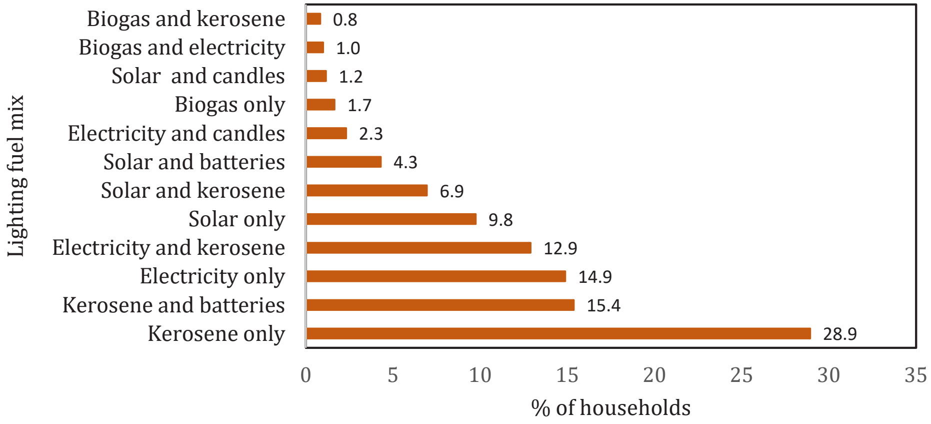

Figure 5. Proportion of sample households by lighting fuel mix

Although these results portray a 'multiple fuel use' behaviour of many of the households, several supply-side problems might have also plaid a major role. Foremost among these are lack of access to modern and clean energy services, severe shortage and unreliability of electricity supply, lack of affordable electric cooking and Injera-baking appliances, lack of private sector investment in the rural energy sector, and inefficiencies in modern energy production, distribution, and utilization. As a result, even when rural households are connected to the grid, the electricity supply is insufficient to meet their basic energy needs due to frequent power outages. The energy shortage for solar users, on the other hand, comes mainly from the limited capacity and poor quality of the solar PV systems and lanterns, intermittent power generation, and low battery capacity.

3.3. Factors influencing rural household's primary cooking fuel choices

Pearson's Chi-square test was used to determine the relationship between household cooking fuel choices and important explanatory variables as shown in Table 5.

Table 5. Pearson's Chi square (χ^2) test of association between household characteristics and primary cooking fuel choices in the study areas

Variable	Category	[1]N (601)	$\chi2$ stat	df	P - value	Cramer's V
Gender	Male	505	3.59	3	0.280	–
	Female	96				
Age	18–29	6	7.34	12	0.601	–
	30–39	113				
	40–49	228				
	50–60	169				
	> 60	89				
Location (district)	Aleta wondo	189	16.88**	9	0.0490	0.105
	Boloso-sore	204				
	Cheha	130				
	Mirab-abaya	78				
Household size	< 3	37	106.31***	9	0.000	0.241
	3–6	290				
	7–10	250				
	> 10	24				
Education level	No formal education	161	8.57	9	0.477	–
	0-4	120				
	5-8	210				
	> 9	110				
Household gross cash income (ETB/year)	< 20,000	268	102.15***	12	0.000	0.328
	20,000 –40,000	119				
	40,000 –60,000	108				
	60,000 –80,000	66				
	> 80,000	40				
Main occupation (source of livelihood)	Cash cropping	194	30.28***	12	0.002	0.123
	Food cropping	157				
	Crop-livestock mixed	145				
	Off-farm activities	79				
	Small private business	30				
Distance to wood source (round trip), minutes	< 20 min.	194	52.93***	9	0.000	0.168
	20 – 40 min.	143				
	40 – 60 min.	208				
	> 60 min.	56				
Grid connection	Yes	194	6.68	3	0.082	–
	No	407				
Biogas ownership	Yes	32	39.95***	3	0.000	0.234
	No	569				

*** and ** represent statistical significance at $p < 0.01$ and $p < 0.05$, respectively.

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[1] Four sample households that use dung-cakes and kerosene as primary cooking fuel are not included.

The Chi-square analyses for gender ($\chi2 = 3.59$, $P = 0.280$) and age ($\chi2 = 7.34$, $P = 0.601$) of the household head indicated that the relationship between household's primary cooking fuel choice and these two variables is not statistically significant. This is perhaps because other factors such as availability and affordability of fuels vis-á-vis household's income level may have a bigger influence on cooking fuel choice than gender and age. Contrary to our results, previous studies in other developing countries (e.g. Baiyegunhi and Hassan, 2014; Rahut et al., 2014) have shown that younger and female-headed households are more likely to choose clean cooking fuels than male-headed households. However, there is also evidence that female-headed households in rural sub-Saharan Africa are more likely to use fuelwood compared to male-headed households as they are more likely to be poor (Köhlin et al., 2012; Mbaka et al., 2019).

The Chi-square test for location ($\chi2 =16.88$, $P = 0.049$) showed that the association between household's location (district) and type of cooking fuel used is significant ($p < 0.05$). This is because the four rural districts are characterized by varying agro-climatic conditions, farming systems, and resource endowments. This variation can influence the availability of fuel, income level of the household, and access to modern energy sources; thereby influencing the choice of cooking fuels.

The Chi-square test for income ($\chi2 = 102.15$, $P = 0.00$) showed that household income level and type of cooking fuels are significantly associated ($p < 0.01$). As illustrated in Figure 6, the use of fuelwood as primary cooking fuel declines as income level increases. Conversely, the use of electricity and charcoal for cooking increases as the income level increases. This suggests that households with higher income tend to prefer clean energy sources (electricity) and more convenient fuels (charcoal) compared with the poorer households who mostly depend on fuelwood and crop residues. These findings are in agreement with other studies in Sub-Saharan Africa (e.g. Mbaka et al., 2019; Menendez and Curt, 2013; Nlom and Karimov, 2015), which reported a statistically significant relationship between household income level and clean cooking fuel use.

Although the choice of fuelwood as primary cooking fuel in the household energy mix does decline with increase in the household income, even the wealthiest households that are connected to the grid have not abandoned the use of fuelwood and agri residues.

Instead, they maintained their energy portfolio and continue to use the traditional fuels (in lower proportions) with modern ones as their income level increases. This is in part due to the unreliability of supply of modern energy sources and dependability of supply of traditional biomass fuels; as well as preferences of taste, convenience of fuel use, and cooking habits of the households. This appears to accord with the fuel-stacking (multiple fuels use) model of energy transition in lieu of the energy-ladder (fuel-switching) model that predicts sharp discontinuity of traditional fuels use as income level increases.

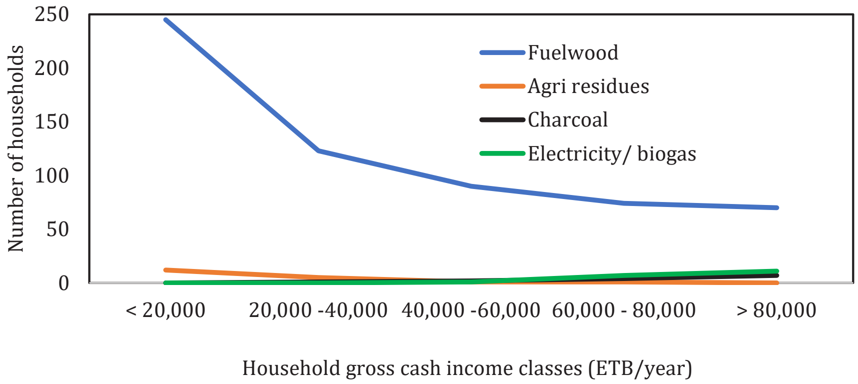

Figure 6. Household income and cooking fuel choice

The Chi-square analysis for household size ($\chi2= 106.31$, $p= 0.000$), and the cooking fuel choice patterns in Figures 7 show that the type of primary cooking fuel is statistically significantly associated with the total family size of the household ($p < 0.01$).

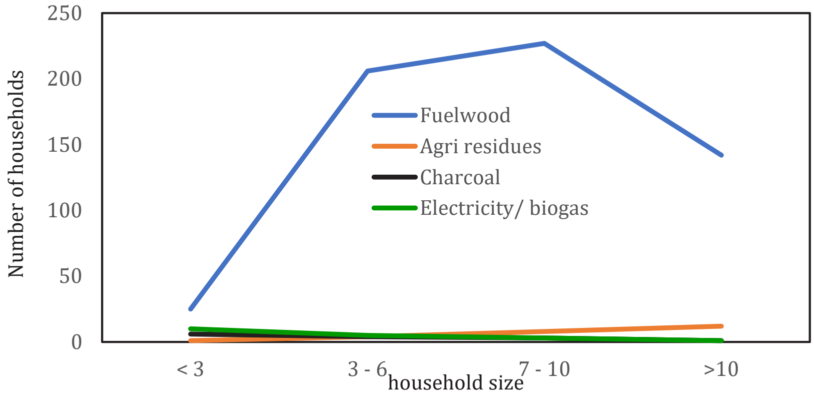

Figure 7. Total household size and cooking fuel choice

It appears that household choice of fuelwood as the primary cooking fuel increases with increase in the household size until a certain peak point (7-10 persons per household) and declines as the family size further increases. The possible explanation for the initial increasing trend is that with an increase in the availability of family labour to collect fuelwood, the use of fuelwood as the main cooking fuel increases. In this respect, Alem et al. (2016) noted that large household size with many females means low opportunity cost of fuelwood collection. The later and declining trend, however, is probably because a further increase in the household size (in light of declining access and availability of fuelwood), compels the household to increase the use of other (complementary) fuels such as agri residues in addition to fuelwood to meet the increased demand for energy. Subsequently, the choice of fuelwood as the primary cooking fuel decreases although it is still part of the domestic energy mix. Similar results were reported by Swarup and Rao (2015) and van der Kroon et al. (2013).

In contrast, the Chi-square test for the education level of the household head ($\chi 2 = 8.57$, P= 0.47) resulted in an insignificant relationship between the education status of the household-head and cooking fuel preferences. This is in contrast to other studies in rural areas of developing countries (e.g. Heltberg; 2004; Makonese et al., 2018; Rahut et al., 2019), which reported that education is among the main drivers to clean cooking fuel choice and transition. The reason for the weak association between cooking fuel choices and education level in this study could be that faced with chronic power shortages and unaffordable electric cooking appliances, even the more educated rural households may have to depend on locally available and affordable cooking fuels.

Concerning the major occupation of the household, however, the Chi-square test ($\chi 2 = 30.28$, P = 0.000) showed that the relationship between household's cooking fuel choice and the main livelihood source is statistically significant ($p < 0.01$). Given the strong relationship between household income and occupation, households that are engaged in cash-crops growing are more likely to use electricity, biogas, and charcoal for cooking compared to the (poorer) cereal croppers. Similar findings were also reported in rural Pakistan (Mirza and Kemp, 2009) and Nigeria (Adeyemi and Adereleye, 2016).

The bulk of the fuelwood consumed in rural Ethiopia is collected from de facto 'open access' state and communal forests, despite these forests are protected by law (Wassie and Adaramola, 2019). The Chi-square analysis for distance to wood source (χ2= 59.93, p= 0.000) and the patterns in Figure 8 reveal that a statistically significant relationship exists between household cooking fuel choice and the distance to wood source (state or communal forests and woodlands).

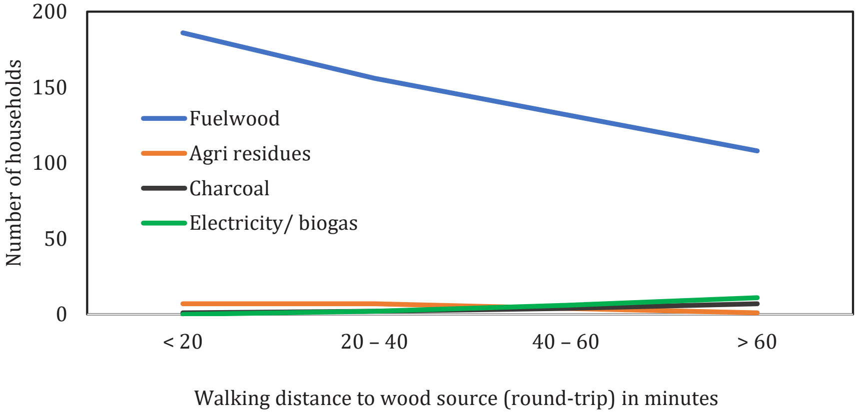

Figure 8. Distance to wood source and cooking fuel choice

As shown in Figure 8, households tend to reduce the use of fuelwood as the main cooking fuel and increase the use of other alternative fuels in the household energy mix as the distance to the wood source increases. This is for the reason that accessibility of wood declines and the cost (labour and time for collection) increases as distance increases. In this line, a study by Jumbe and Angelsen (2011) in Malawi has shown that distance to the wood source was one of the key determinants of fuelwood choice and driving force behind the transition to clean fuels.

The Chi-square test for grid connection (χ2= 6.68, p= 0.082) however indicated that the household's cooking fuel choice is not significantly associated with access to electricity. Despite 32% of the household being connected to the grid, only a few households use electricity as primary cooking fuel. As noted earlier, the main reason for this is that the cost of electrical cooking appliances is very high compared to the income levels of the rural poor. Moreover, the current electricity supply in Ethiopia in general and in rural areas, in particular, is faced with serious power shortage and intermittency problems., As a result, grid connection has not led to significant energy substitution for cooking, at least for now. Other studies (e.g. Heltberg, 2004; Makonese et al., 2018), however, have shown a strong link between access to electricity and clean cooking.

A statistically significant relationship was observed between the primary cooking fuel choice of rural households and ownership of biogas plants ($\chi2= 39.95$, $p= 0.00$). This is despite a significant number of the biogas plants installed are currently non-functional. The result may suggest that if uninterrupted and efficient utilization of biogas plants can be achieved, the technology can play a considerable role in inducing substantive cooking energy substitution and (transition) in rural Ethiopia. Yet, this is not the case now.

Other factors that are not included in the Chi-square tests but were found to have some level of influence in determining household's cooking fuel choice were the price of fuel, compatibility to local cooking habits, food taste, and ease of use. From the direct kitchen cooking observational studies, it was found that rural households generally prefer to use cheaper fuels (fuelwood compared to charcoal), and fuels that fit to the locally available cooking stoves (solid biomass fuels rather than electricity and LPG). Interestingly, it was also found that households generally prefer to prepare some meals ('Wot) and coffee with solid biomass even when they have an electric stove for the reason of better taste.

3.4. Determinants of household energy sources for lighting: Estimation of Multivariate Probit (MVP) Model

Determinants of household energy choices for lighting were estimated by using the Multivariate Probit model. The five binary outcome dependent variables included in the model are kerosene, batteries, electricity, solar, and biogas. Table 6 shows the pairwise correlation coefficients and relationships between these five energy choices. Table 7 illustrates the regression outputs of the MVP model. The Wald Chi^2 (70) = 576.49, Prob > chi^2 = 000 is statistically significant at 1% significance level, which indicates that the overall model is significant, and the explanatory power of the variables included in the model is satisfactory. The likelihood ratio test $Chi^2(10) = 41.56$, Prob > Chi^2 = 0001 is also significant at 1% significance level. This means that the null hypothesis that the choice of each of the five lighting energy options is independent ($\rho_{ij} = 0$) is rejected. The result highlights the goodness of fit of the MVP model and the interdependence among household lighting energy choices, and therefore the appropriateness of the application of the MVP model for the lighting energy choices analysis.

Table 6. Correlation results of the five lighting energy choices

Variable correlations	Coefficients	Standard error	Z	P value
Kerosene and electricity	−0.396	0.181	−2.52**	0.014
Kerosene and batteries	0.432	0.135	2.67***	0.008
Kerosene and solar	−0.275	0.141	−1.98**	0.048
Kerosene and biogas	−0.193	0.143	−1.69	0.114
Batteries and electricity	−0.489	0.194	−3.07***	0.002
Batteries and solar	−0.203	0.150	−1.58	0.165
Batteries and biogas	−0.232	0.198	−1.37	0.209
Electricity and solar	−0.284	0.109	−2.16**	0.046
Electricity and biogas	0.016	0.013	0.098	0.997
Solar and biogas	−0.018	0.019	−0.13	0.905

Likelihood ratio test of (rho=0): $chi^2(10) = 41.56$

Prob > $chi^2 = 0.0001$

Significance level: ***1% and **5%

Generally, the correlation coefficients in Table 6 depict a positive relationship between traditional (dirty) fuels and a negative relationship between traditional fuels and clean energy sources. A negative and significant relationship is observed between the choice of electricity and kerosene, indicating a substitution effect between these two energy sources. Similarly, a negative and significant correlation is observed between kerosene and solar, and between electricity and batteries. This suggests the existence of a strong substitution effect between modern/clean and dirty lighting fuels; such that a household that uses solar PV or connected to the grid is less likely to choose kerosene and dry-cell batteries as primary lighting energy sources. Interestingly, a negative and significant correlation was observed between the use of electricity and solar, suggesting that solar lighting can be as competent as (interchangeable with) grid electricity.

On the other hand, a positive and significant correlation was noted between kerosene and batteries, indicating the existence of complementarity between the two dirty fuels, especially in off-grid areas. The positive relationship between biogas and electricity use may indicate that households prefer to use a combination of clean lighting sources when either of the sources is unable to provide sufficient energy. Overall, the correlation results reiterate that households depend on multiple energy sources for lighting and the decision over which energy source to use is non-mutually exclusive.

The results in Table 7 show that household's energy choices for lighting are significantly influenced by a wide range of demographic, economic, and non-economic factors. The most important factors are education level, household size, location, distance to market, access to road, income level, and access to credit facility. The coefficients signify the influence of each factor on each of the five lighting energy choices (dependent variables).

Table 7. Multivariate probit estimates of determinants of household energy choices for lighting

Explanatory variables	Kerosene	Batteries	Electricity	Solar	Biogas
[a]Gender of HH head (1= Female)	0.0273	0.015	−0.033	−0.314	−0.145
	(0.144)	(0.012)	(0.040)	(0.205)	(0.126)
Age of HH head	0.085**	0.029	0.017	−0.070	−0.280**
	(0.089)	(0.045)	(0.024)	(0.552)	(0.103)
Education level of HH head	−0.114**	−0.109	0.235**	0.159	0.393***
	(0.180)	(0.106)	(0.215)	(0.009)	(0.315)
Total HH size	0.190***	0.169**	−0.011	−0.188**	0.173**
	(0.029)	(0.018)	(0.028)	(0.223)	(0.027)
Number of family members enrolled in school	−0.026	−0.018	0.124	0.293***	0.360**
	(0.167)	(0.013)	(135)	(0.300)	(0.162)
Gross annual cash income	−2.367***	−0.808**	1.389**	2.413***	3.811***
	(2.306)	(0.762)	(0.600)	(1.190)	(1.480)
Landholding size	−0.163**	−0.120	0.149	0.226**	0.195**
	(0.170)	(0.137)	(0.107)	(0.307)	(0.125)
Cattle holding size	−0.053	−0.024	0.020	0.023	0.215**
	(0.025)	(0.015)	(0.010)	(0.004)	(0.085)
Distance to market	0.204***	0.069	−0.119	−0.209***	−0.132
	(0.068)	(0.065)	(0.088)	(0.168)	(0.143)
Distance to road	0.283***	0.147	−0.238***	−0.198**	−0.127
	(0.070)	(0.067)	(0.170)	(0.106)	(0.074)
[a]Access to credit facility	−0.074	−0.019	0.114	0.236***	0.319***
	(0.095)	(0.068)	(0.166)	(0.035)	(0.131)
[b]Location: Boloso-sore	1.909***	1.201**	−1.285***	−1.127**	0.092
	(0.312)	(0.243)	(0.245)	(0.110)	(0.055)
[b]Location: Cheha	−0.148	−0.015	−0.029	0.307*	0.018
	(0.243)	(0.027)	(0.024)	(0.120)	(0.045)
[b]Location: Mirab-abaya	−0.219**	−0.077	1.156***	−0.199	−0.322**
	(0.080)	(0.204)	(0.175)	(0.205)	(0.177)
Constant	−2.977***	0.366	−1.056***	−1.005**	0.242
	(1.674)	(0.170)	(0.776)	(1.004)	(0.215)

Number of observations = 605
Log-likelihood function= −1092.26
Wald Chi^2, χ2(70) =576.49
Prob > chi^2 = 0.000
(): Figures in parentheses are standard errors
Significance level: ***1% and **5%
[a] Dummy variable
[b] Location dummies: Aleta-wondo is the reference category

3.4.1. Demographic and human capital factors

Gender: The coefficients of the dummy variable gender (female) are insignificant for all the five lighting energy choice options, implying that gender of the household head may not affect the household's lighting energy choices significantly. This might be because other factors such as household income level and access to clean energy sources have a greater influence on the decision over lighting energy choices than gender. However, other studies (e.g. Berhe et al., 2017; Rahut et al., 2017) have found that female-headed households are more likely to choose cleaner and renewable lighting energy sources compared to male-headed households.

Age: The age of the household head is positively and significantly related to kerosene use, and negatively and significantly associated with biogas use. The implication is that younger households with better education and awareness are more likely to use clean and modern energy for lighting whereas older households may prefer to continue using traditional kerosene fuels and batteries. In agreement with this finding, studies by Ali et al. (2019) and Mbaka et al. (2019) also indicated that household head's age is negatively and significantly associated with clean energy use.

Education level: The educational level (number of years of schooling completed) of the household head is positively and significantly associated with the choice of electricity and biogas, and negatively and significantly associated with kerosene use. This indicates that with increase in the household head's education level, the probability of choice of modern and renewable energy for lighting increases. Previous studies have also found a positive and significant relationship between clean lighting energy use and education level of the household-head (e.g. Lay et al., 2012; Rahut et al., 2017).

Household size: The coefficients of household size are positive and significant for kerosene, batteries, and biogas; and negative and significant for solar. This means that households with larger family sizes are more likely to use kerosene and batteries while those with fewer members tend to use solar lighting. The reason could be that larger family size means more lighting energy demand which may not be met by the limited capacity of (affordable) solar PVs/lanterns and intermittent electricity supply. Hence, households with large family sizes tend to prefer kerosene than solar.

The positive and significant association between biogas use and household size is likely from the high labour demand of biogas operation. A positive and significant relationship is observed between the number of children enrolled in school; and the use of solar and biogas for lighting. This may indicate the importance of clean, safe, and quality lighting for students in the family, as a driving force for the use of biogas and solar technologies.

3.4.2. Economic (income) factors

Household income: The coefficients of income level of the household are positive and significant for electricity, solar and biogas; and negative and significant for kerosene and batteries. This indicates that wealthier households are more likely to choose clean and modern energy sources for lighting compared to poorer ones who mostly depend on kerosene and batteries. The results reaffirm that the economic status of the household is one of the major drivers of the decision for energy transition towards modern and clean sources. Several other studies have also reported that income plays a pivotal role in the rural household energy choices in developing countries (Ali et al., 2019; Gaur, 2018; Giri and Goswami, 2017; Rahut et al., 2017).

Land and cattle holdings: The estimated coefficients of landholdings size are positive and significant for solar and biogas; and negative and significant for kerosene. Similarly, the coefficients of cattle holding sizes are positive and significant for biogas. The results signify the importance of household natural and physical capitals on lighting energy choices by affecting the household's income and availability of feedstock (cow-dung) for biogas production. A study by Kabir et al (2013) in Bangladesh also showed that cattle holding positively and significantly influenced household use of biogas for lighting.

Access to credit: the coefficients of access to credit services are positive and significant for solar and biogas use, highlighting that households who have access to credit facilities are more likely to use clean energy sources than those without. The result supports the finding of Berhe et al. (2017) in rural northern Ethiopia which showed that access to credit financing facilities positively and significantly influenced biogas adoption. These findings have important policy implications in the sense that improving the access to credit service of rural households can increase the use of biogas and solar for lighting (and possibly the use of modern and clean cooking fuels and technologies) by alleviating the financial constraints needed to adopt and operate the technologies.

3.4.3. Non-income factors

Distance to market: The results in Table 7 show that the probability of kerosene use increases with increase in the distance between the household's home and local market. Conversely, households residing near markets are more likely to use solar PVs/lanterns. This is because, in the context of Ethiopia, access to solar products and grid connection is higher in areas closer to market (town) than in remote villages. As such, households distant to market are mostly dependent on kerosene for lighting. The finding supports a recent study by Gaur (2018) in India which showed that proximity to markets was one of the main factors that positively influenced household's use of modern lighting fuels.

Distance to road (access to transport): Distance to road is positively and significantly associated with kerosene use, and negatively and significantly related to electricity, and solar use. This suggests that households living in short distance to road access are more likely to use clean lighting fuels such as electricity and solar compared with those that live in areas with limited road connectivity. One of the main reasons for this is that the cost of biogas and solar use (transportation cost in particular) is higher for households that have limited access to road networks compared with those living closer to the road. Moreover, in most cases, grid power lines in Ethiopia follow road networks for ease of maintenance and service delivery. This result is in congruence with a recent study by Ali et al. (2019) in rural Pakistan which showed that households closer to road networks were more likely to use electricity than in afar areas.

Geographic location: The results in Table 7 for location (district) indicate that when compared with the households in Aleta-wondo district, the use of electricity for lighting is positively and significantly related to households in Mirab-abaya; and negatively and significantly associated with Boloso-sore district. By contrast, households in Boloso-sore district are more likely to use kerosene than those in Aleta-wondo. Conversely, compared to Aleta-wondo district, solar energy use is positively and significantly related to Cheha district; and biogas use is negatively and significantly related to Mirab-abaya. The results signify that the location of the household plays a key role in determining the choice of lighting energy by influencing household income, access to market, and access to modern energy and clean energy sources, and technologies.

Apparently, in Boloso-sore where the average annual gross income of a household is the lowest, households may rather use kerosene than purchase solar PVs as they could not afford the high cost. Conversely, the use of solar PVs is highest in Cheha district partly due to the better diffusion of solar products in the area as a result of the well-established solar market and proximity to the capital city Addis Ababa (main distribution centre). The implication is that the success of rural household energy transition greatly depends on location-specific variables and the degree to which these variables are addressed in energy planning.

4. Conclusions

The findings from the present study indicated that the cooking energy portfolio of rural households in southern Ethiopia is heavily dominated by traditional solid biomass fuels particularly fuelwood. By contrast, kerosene, electricity, solar, biogas, and batteries are used as important energy sources for lighting. The results confirm that with increase in the household's income level, education, access to renewable energy sources, access to market and road connection; the probability of choice of cleaner and modern cooking, and lighting fuels increases. However, it was also found that high-income level and grid connection have not led households to completely forgo the use of traditional biomass, and fossil fuels altogether. Instead, with increase in income level and access to modern energy sources, households continued to utilize traditional fuels alongside modern ones for complementarity advantages and other reasons. This pattern is in line with the 'fuel-stacking' model of energy transition rather than the energy-ladder model of complete fuel-switching following significant increase in income level. However, it should also be noted that the absence of full-fledged energy transition could be, in part, due to several supply-side problems including limited access and unreliable supply of modern energy services, and lack of affordable electrical cooking and baking devices, to mention a few. Overall, the study highlights that while income remains a key factor, several non-income factors also play a major role in determining household energy choices and transition in the context of rural Sub-Saharan Africa. The implication is that policymakers and energy planners in Ethiopia and sub-Saharan Africa may need to take into account these diverse factors when designing energy policies and energy supply projects to rural areas.

5. References

Adeyemi, P.A., Adereleye, A. (2016). Determinants of Household Choice of Cooking Energy in Ondo State, Nigeria. J of Econo. and Sustain. Development, 7(9).

Alem, Y., Beyene, A.D., Köhlin, G., Mekonnen, A. (2016). Modelling Household Cooking Fuel Choice: A Panel Multinomial Logit Approach. Energy Economics, 59 (C): 129-137.

Ali, A., Rahut, D.B., Mottaleb, K.A., Aryal, J.P. (2019). Alternate energy sources for lighting among rural households in the Himalayan region of Pakistan: Access and impact. Energy & Environment, 30(7).

Baiyegunhi, L.J.S., Hassan, M.B. (2014). Rural household fuel energy transition: Evidence from Giwa LGA Kaduna State, Nigeria. Energy for Sustainable Development, 20: 30–35.

Behera, B., Rahut, D.B., Jeetendra, A., Ali, A. (2015). Household collection and use of biomass energy sources in South Asia. Energy, 85:468-480.

Berhe, M., Hoag, D., Tesfay, G., Keske, C. (2017). Factors influencing the adoption of biogas digesters in rural Ethiopia. Energy, Sustainability and Society, 7(10).

Campbell, B.M., Vermeulen, S.J., Mangono, J.J., Mabugu, R. (2003). The energy transition in action: urban domestic fuel choices in a changing Zimbabwe. Energy Policy, 31(6):553–562.

Cochran, W.G. (1977). Sampling Techniques, Wiley, New York.

CSA. (2013). Federal Democratic Republic of Ethiopia (FDRE), Central Statistical Agency. Population Projection for All Regions from 2014 – 2017. Addis Ababa. https://www.academia.edu/30252151/Federal_Democratic_Republic_of_Ethiopia_Central_Statistical_Agency_Population_Projection_of_Ethiopia_for_All_Regions_At_Wereda_Level_from_2014_2017(Accessed 03.03.19).

CSA. (2011). Central Statistical Agency Ethiopian of Ethiopia. Welfare Monitoring Survey Report of 2011; Addis Ababa. http://catalog.ihsn.org/index.php/catalog/3124 (Accessed 08.03.19).

Edwards, Y. D., Allenby, G. M. (2003). Multivariate analysis of multiple response data. Journal of Marketing Research, 40:321–334.

FDRE. (2016). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan II (GTP II): 2015/16 – 2019/20. National Planning Commission; Addis Ababa, Ethiopia 2016.

FDRE. (2010). Federal Democratic Republic of Ethiopia, Growth and Transformation Plan I (GTP I): 2010/11 – 2014/15. Ministry of Finance and Economic Development. Addis Ababa, 2010. https://www.undp.org/content/dam/unct/ethiopia/docs/GTP%20English%20Vol1%20(1).pdf (Accessed 27.04.19).

Gaur, V. (2018). Determinants of Household's Modern Cooking and Lighting Energy Transition in Rural India- Exploring Household's Activities and Its Interactions with Other Households. ZEF-Discussion Papers on Development Policy No. 256 University of Bonn - Centre for Development Research (ZEF).

Mekonnen, A., Kassie, M., Köhlin, G. (2012). Urban energy transition and technology adoption: The case of Tigrai, Ethiopia. Energy Economics, 34 (2): 410-418.

Giri, M., Goswami, B. (2017). Determinants of household's choice of energy for lighting in Nepal. Economics and Business Letters, Oviedo University Press, 6(2): 42-47.

Golob, T.F., Regan, A.C. (2002). Trucking industry adoption of information technology: a structural multivariate discrete choice model. Transp Res Part C: Emerg Technol, 10:205–228.

Guta, D.D. (2014). Effects of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. Energy Policy, 75: 217-227.

Guta, D.D. (2012). Assessment of biomass fuel resource potential and utilization in Ethiopia: sourcing strategies for renewable energies. Int J of Renewable Energy Research, 2(1):134–136.

Heltberg, R. (2005). Factors determining household fuel choice in Guatemala. Environ Dev Econ, 10:337–61.

Heltberg, R. (2004). Fuel switching: evidence from eight developing countries. Energy Econ, 26:869–87.

Hosier, R.H., Dowd, J. (1987). Household fuel choice in Zimbabwe: an empirical test of the energy ladder hypothesis. Resour. Energy, 9(4):347–361.

IEA. (2018a). World Energy Outlook 2018. International Energy Agency, IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2018 (Accessed 12.5. 19).

IEA. (2018b). International Energy Agency. Energy statistics Ethiopia 1990 – 2016. https://www.iea.org/statistics/?country=ETHIOPIA&year=2016&category=Energy%20supply&indicator=TPESbySource&mode=chart&dataTable=BALANCES (Accessed 28.06.19).

Jumbe, C.B.L., Angelsen, A. (2011). Modelling choice of fuelwood source among rural households in Malawi: A multinomial probit analysis. Energy Economics. Energy Economics, 33: 732–738.

Kabir, E., Kim, K.H., Szulejko, J.E. (2017). Social Impacts of Solar Home Systems in Rural Areas: A Case Study in Bangladesh. Energies, 10(10).

Kabir, H., Yegbemey, R.N., Bauer, S. (2013). Factors determinant of biogas adoption in Bangladesh. Renew Sustain Energy Rev, 28:881–889.

Kebede, B., Bekele, A., Kedir, E. (2002). Can the urban poor afford modern energy? The case of Ethiopia. Energy Policy. 30(11):1029–1045.

Köhlin, G., Sills, E.O., Pattanayak, S.K., Wilfong, C. (2012). Energy, Gender and Development What are the Linkages? Where is the Evidence? Policy Research Working Paper No 5800. The World Bank.

Lay, J., Ondraczek, J., Stoever, J. (2012). Renewables in the Energy Transition: Evidence on Solar Home Systems and Lighting-Fuel Choice in Kenya. GIGA working papers No 198.

Lemenih, M., Bongers, F. (2011). Dry Forests of Ethiopia and Their Silviculture. In: Günter, S., Weber, M., Stimm, B., Mosandl, R. (eds). Silviculture in the Tropics. Tropical Forestry Vol (8), Springer, Berlin, Heidelberg.

Makonese, T., Ifegbesan, A.P., Rampedi, I.T. (2018). Household cooking fuel use patterns and determinants across southern Africa: Evidence from the demographic and health survey data. Energy & Environment, 29 (1).

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

Mbaka, C.K., Gikonyo, J., Kisaka, O.M. (2019). Households' energy preference and consumption intensity in Kenya. *Energy, Sustainability and Society*, 9(20).

McHugh, M.L. (2013). ''The Chi-Square Test of Independence.'' Biochemia Medica, 23: 143–149.

Mekonnen, A., Köhlin, G. (2009). Determinants of Household Fuel Choice in Major Cities in Ethiopia. Working papers in economics No 399, University of Gothenburg.

Menendez, A., Curt, M.D. (2013). Energy and socio-economic profile of a small rural community in the highlands of central Tanzania: a case study. Energy Sustain Develop., 17:201-209.

Mirza, B., Kemp, R. (2011). Why the Rural Rich Remain Energy Poor Consilience: The Journal of Sustainable Development, 6 (1):133–155.

Mondal, A.H., Bryan, E., Ringler, C., Mekonnen, D., Rosegrant, M. (2018). Ethiopian energy status and demand scenarios: Prospects to improve energy efficiency and mitigate GHG emissions. Energy, 149:161-172.

MoWE. (2012). Federal Democratic Republic of Ethiopia, Ministry of Water and Energy Scaling - Up Renewable Energy Program Ethiopia. Addis Ababa. https://www.oecd.org/env/cc/TADELE_FDRE%20Ethiopia%20Scaling%20-%20Up%20Renewable%20Energy%20Program%202012.pdf (Accessed 7.2.19).

Murphy, J.T. (2001). Making the energy transition in rural East Africa: is leapfrogging an alternative? Technological Forecasting & Social Change, 68 (2): 173-193.

Nansairo, A., Patanothai, A., Rambo, A.T., Simaraks, S. (2011). Climbing the Energy Ladder or Diversifying Energy Sources? The Continuing Importance of Household Use of Biomass Energy in Urbanizing Communities in Northeast Thailand. Biomass and Energy, 35 (10): 4180-4188.

Narain, U., Gupta, S., Veld, K. (2008). Poverty and resource dependence in rural India. Ecol Econ 66(1):161–176.

Nlom, J.H., Karimov, A.A. (2015). Modelling fuel choice among households in Northern Cameroon. Sustainability, 7: 9989-9999.

Rahut, D.B., Ali, A., Mottaleb, K.A., Aryal, J.P. (2019). Wealth, education and cooking-fuel choices among rural households in Pakistan. Energy Strategy Reviews, 24:236-243.

Rahut, D.B., Behera, B., Ali, A. (2017). Factors determining household use of clean and renewable energy sources for lighting in sub-Saharan Africa. Renewable and Sustainable Energy Reviews, 72(C):661-672.

Rahut, D.B., Das, S., De Groote, H., Behera, B. (2014). Determinants of household energy use in Bhutan. Energy, 69: 661–672.

Schlag, N., Zuzarte, F. (2008). Market barriers to clean cooking fuels in Sub-Saharan Africa: a review of literature. Working paper. Stockholm Environment Institute. https://www.seiinternational.org/mediamanager/documents/Publications/Climate/market_barriers_clean_cooking_fuels_21april.pdf. (Accessed 19.01.19).

Swarup, V.A., Rao, K.R. (2015). An Econometric Approach to Analysis of Trends and Patterns of Household Fuel Choices in India. Indian Economic Review, 50(1):105-129.

Tucho, G. T. (2016). Improving the energy system for a rural community in developing countries: Challenges and sustainable opportunities in using renewable energy resources in Ethiopia. University of Groningen. https://www.rug.nl/research/portal/files/38569020/Chapter_2_.pdf (Accessed 17.03.19)

Tucho, G.T., Weesie, P.D.M., Nonhebel, S. (2014). Assessment of renewable energy resources potential for large scale and standalone applications in Ethiopia. Renew and Sustain Energy Reviews, 40: 422–431.

Van der Kroon, B., Brouwer, R., Van Beukering, J.H.P. (2013). The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis. Renewable and Sustainable Energy Reviews, 20:504-513.

Wassie, Y.T., Adaramola, M.S. (2019). Potential environmental impacts of small-scale renewable energy technologies in East Africa: A systematic review of the evidence. Renew. Sustain. Energy Reviews, 111: 377-391.

World Bank. (2017). Sustainable Energy for All (SE4ALL): Access to electricity, rural (% of rural population) in Ethiopia in 2017. https://data.worldbank.org/indicator/eg.elc.accs.ru.zs (Accessed 21.03.19)

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