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

Philosophiae Doctor (PhD)
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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

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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 ($\chi 2$) 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.*

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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).

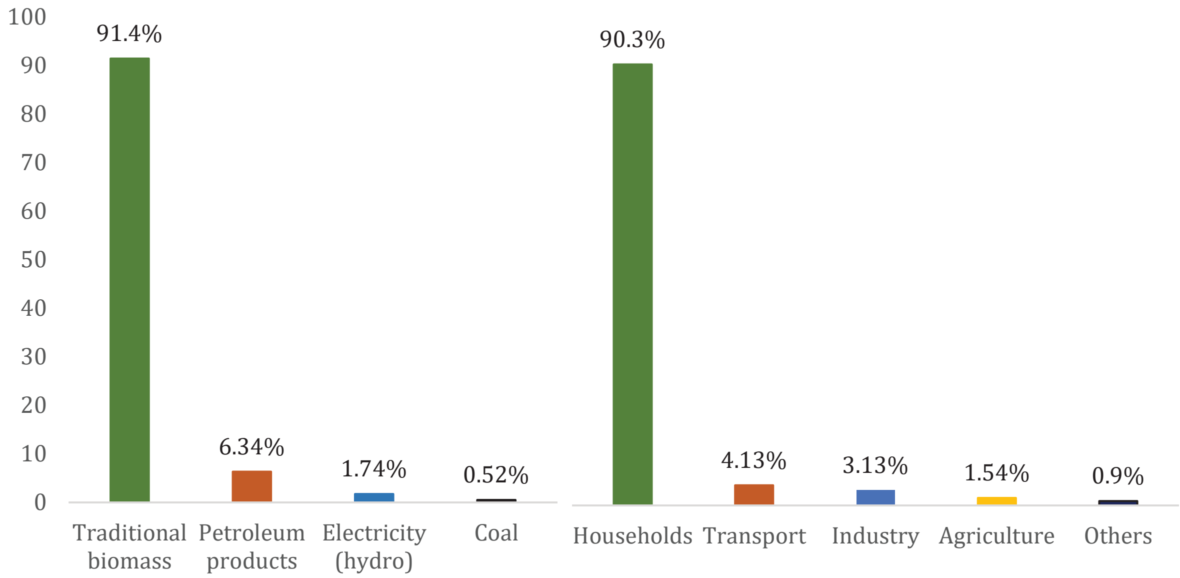

Figure 1a. Share of total primary energy supply by source; and Figure 1b share of final energy consumption by sector in Ethiopia in 2016 (IEA, 2018b)

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%.

[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.

[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.

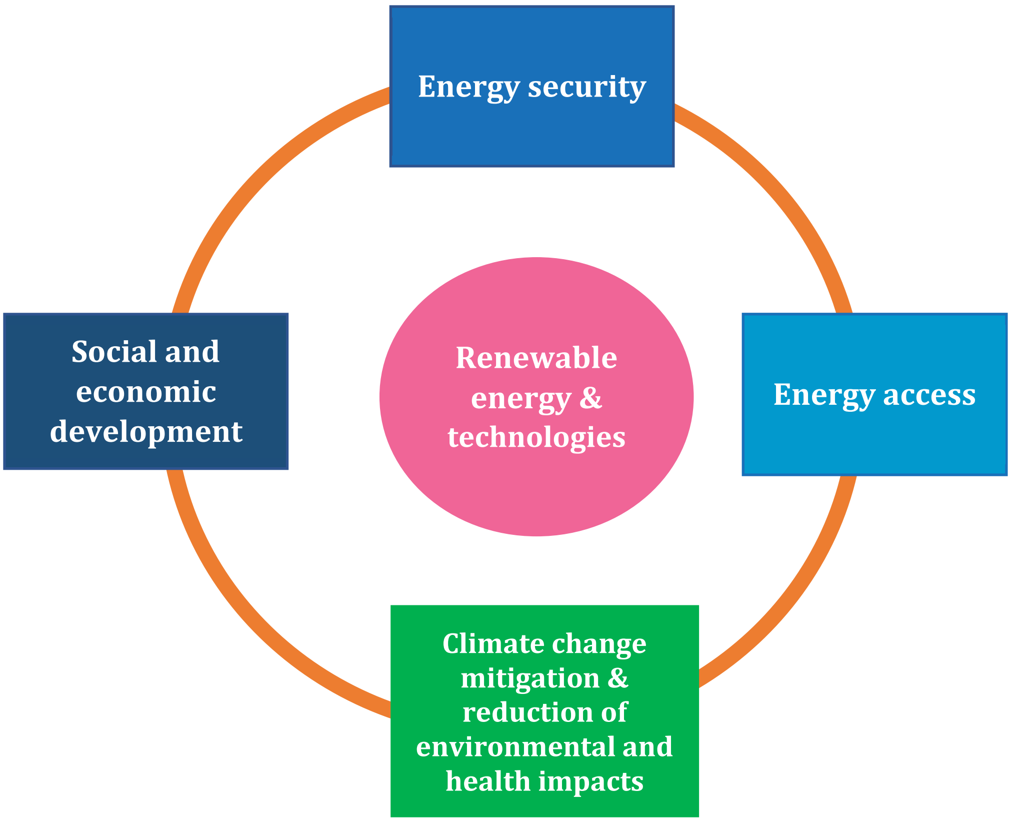

Figure 2. Schematic representation of inter-linkages between RES & Ts; and its energy, economic and environmental effects (based on Owusu et al., 2016)

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).

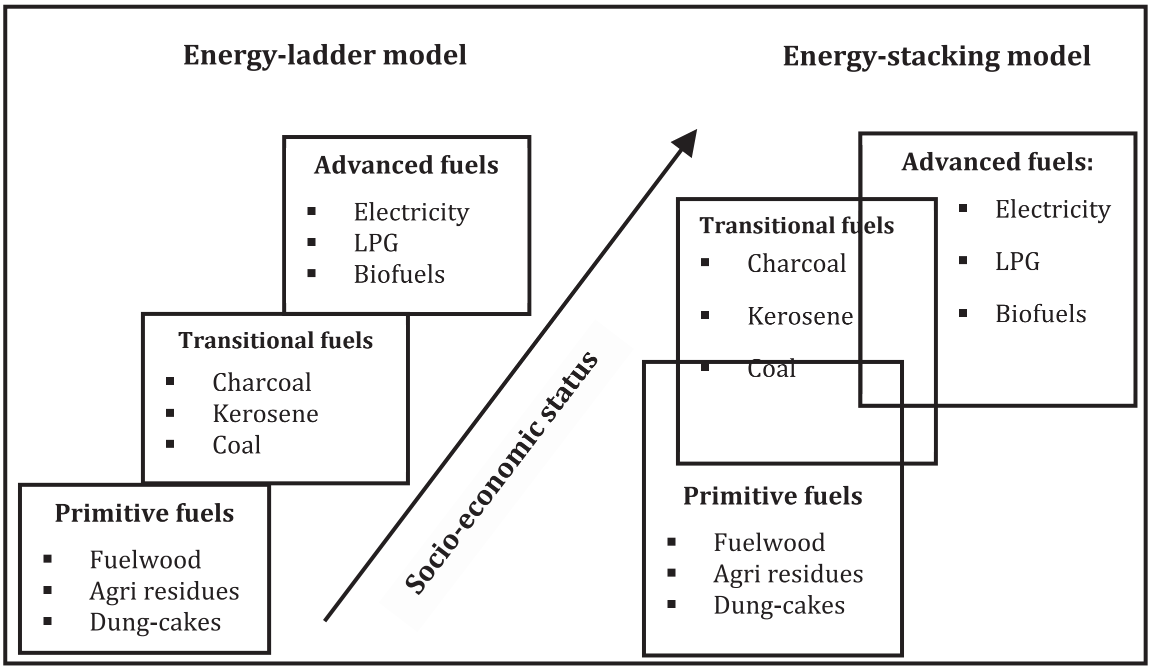

Figure 3. The energy transition process (Based on Schlag and Zuzarte, 2008)

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.

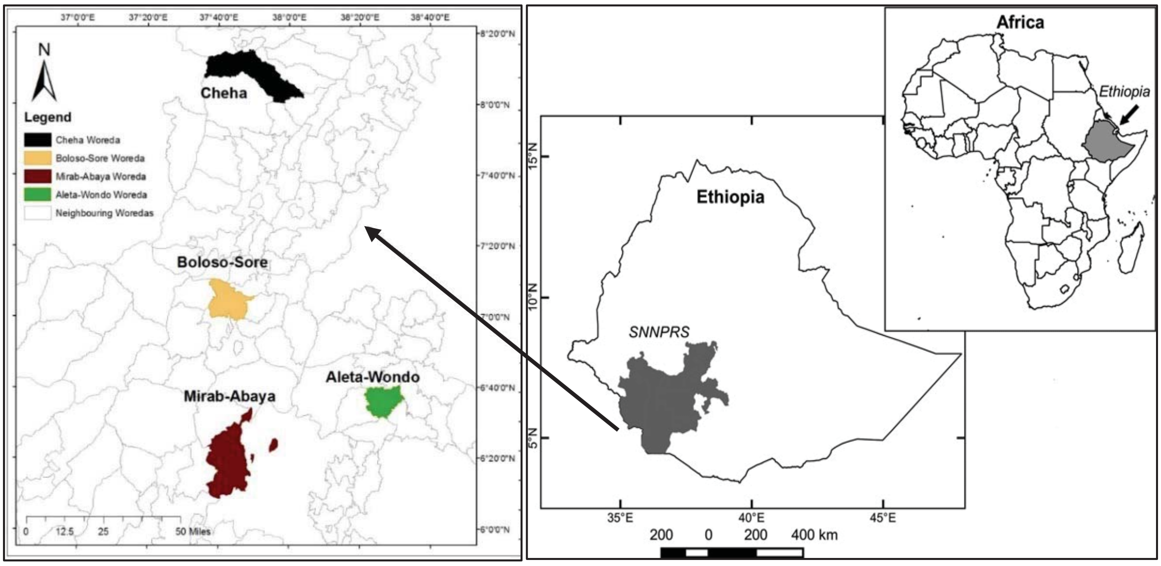

Fig 4. Location map of the SNNPRS and study districts (*woredas*)

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).

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

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

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

[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 ($\chi 2$) 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, ..., y_5 was formulated as:

$$y_i = 1 \text{ if } \beta_i X' + \varepsilon_i > 0$$

and (3)

$$y_i = 0 \text{ if } \beta_i X' + \varepsilon_i \leq 0 \qquad i = 1,2,\ldots 5$$

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.

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.

[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.

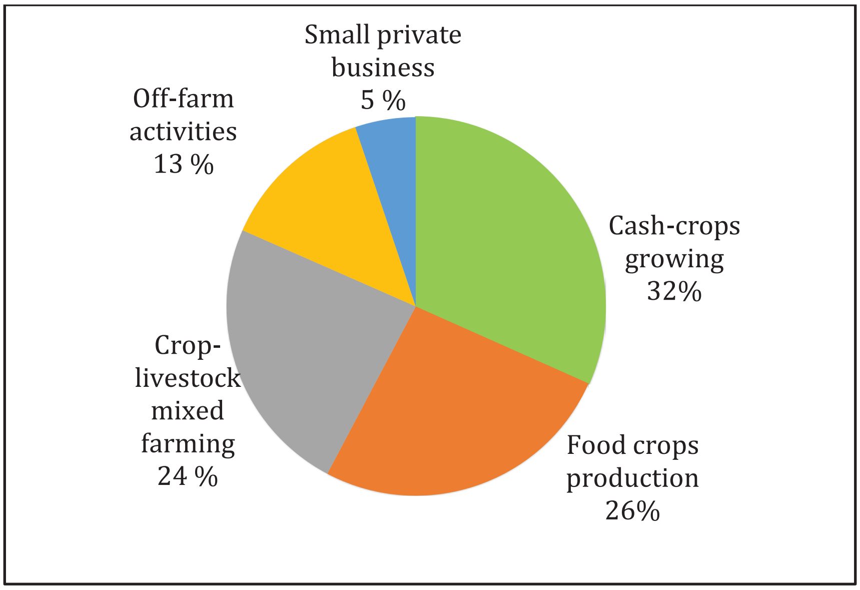

Figure 5. Distribution of sample households by primary occupations (source of income)

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.

[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.

[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.

[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.

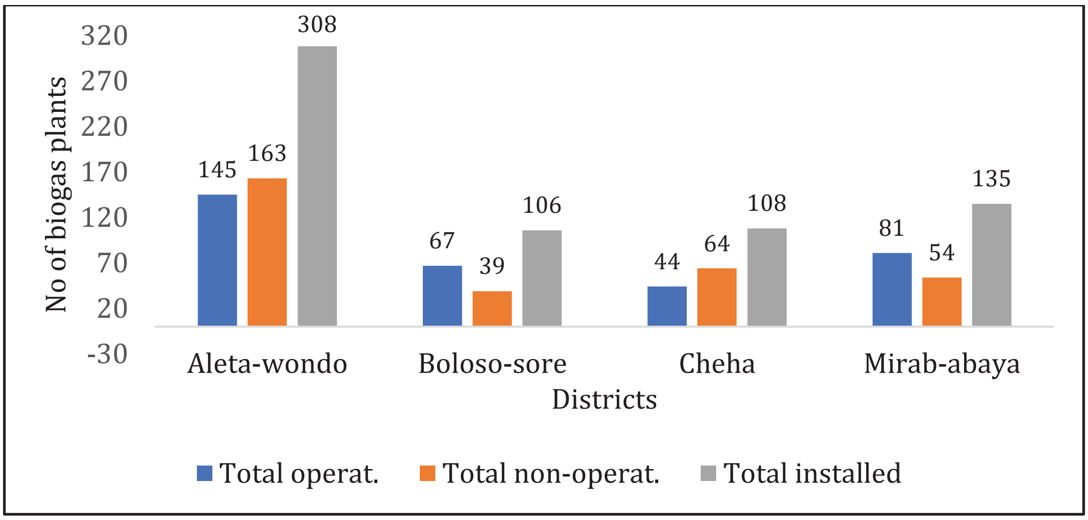

Figure 6. Current operational status of biogas plants installed between 2011 and 2017 in the four districts (based on panel data from district energy offices, 2018)

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.

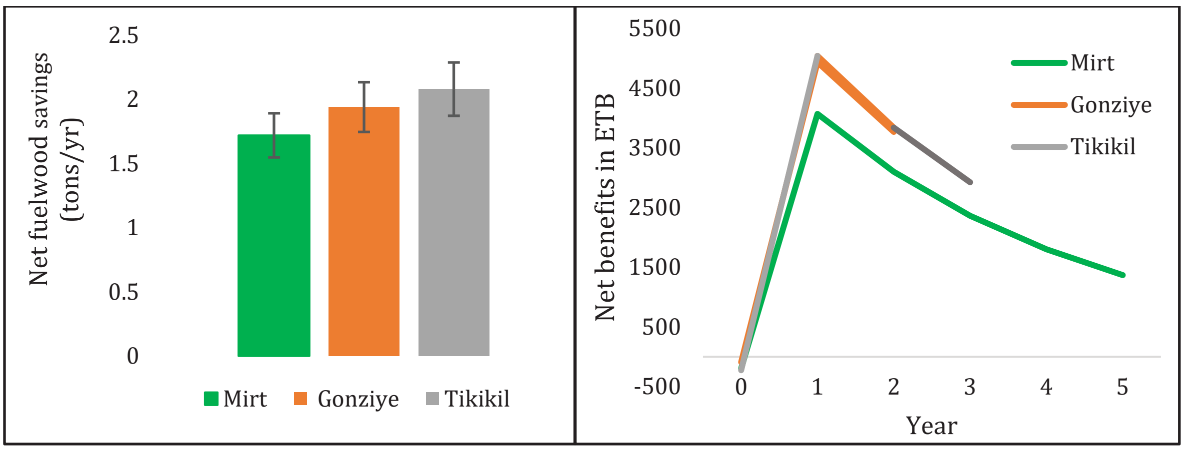

Figure 7a. Total net fuelwood savings (tons/yr) of each stove; figure 7b cash flow of net economic benefits from each stove in ETB.

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.

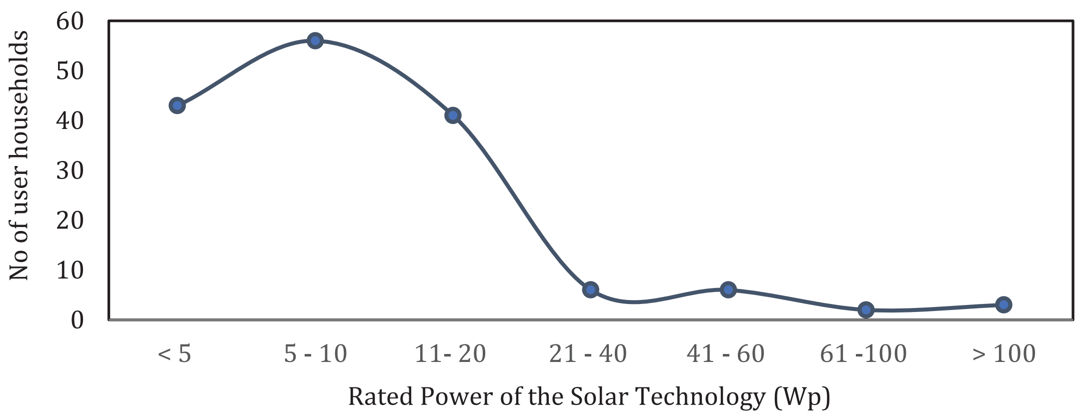

Figure 8. Distribution of solar technologies in the study area by power generation capacity

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				

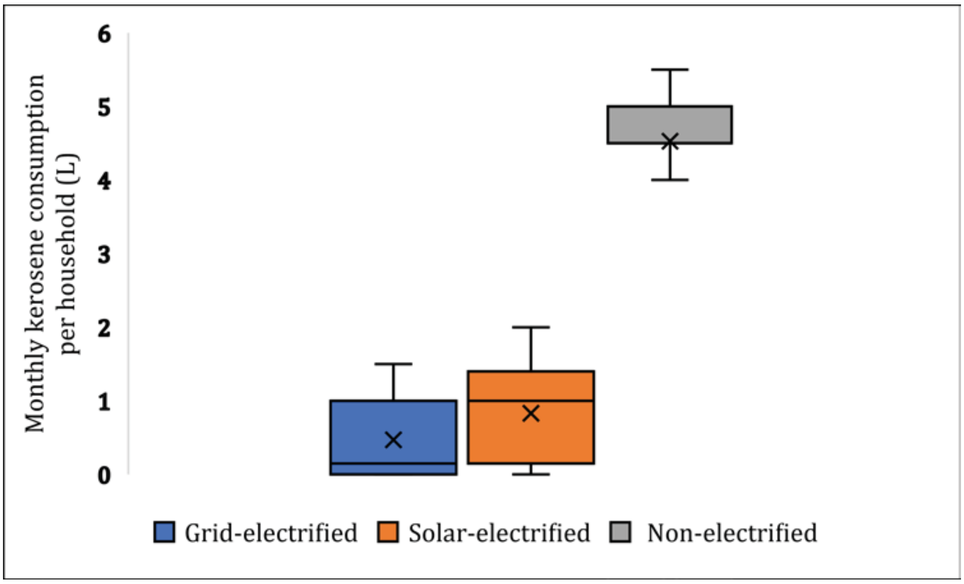

Figure 9. Box plot of mean monthly kerosene consumption by type of electrification

[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).

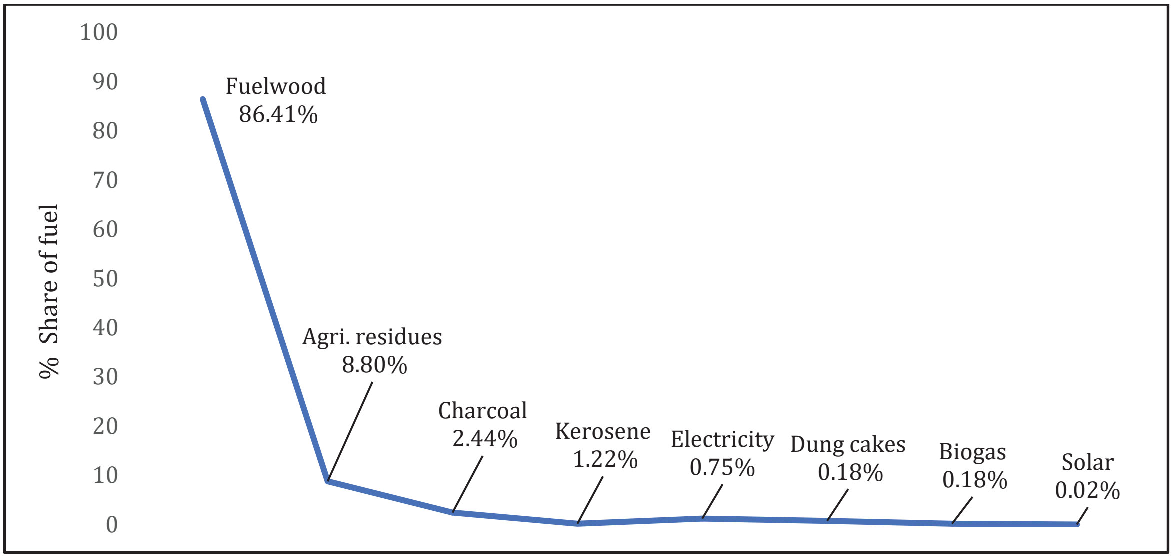

Figure 10. Percent share of the different fuels in the total household energy consumption

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 ($\chi2$) 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.

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