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Abstract

Energy consumption in Ethiopia is based mainly (90%) on the traditional use of biomass for domestic needs, typically using rudimentary cooking stoves. Against this background this study examined the importance of biomass energy use among rural households and evaluated long-term energy security at the national level. To this end, a farm household model was developed to investigate the association between biomass energy use and food security. The study explored the effects of fuelwood scarcity on rural livelihoods through an examination of household decisions regarding the allocation of family labour and expenditures on food and energy. For this purpose the study relied on a panel dataset derived from Ethiopian households. Due to the endogeneity of shadow wages and prices, and to selectivity biases, a Fixed Effect Two-Stage Least Squares model was used with inverse Mills ratios to determine wages and food and energy expenditures. In addition, Seemingly Unrelated Regression and Almost Ideal Demand System analyses were used to estimate the allocation of labour to agriculture, fuelwood collection, and off-farm activities jointly. Discrete household energy decisions were estimated using a multinomial logit model with predicted wages and other determinants. Shadow prices of fuelwood and agricultural fuels were estimated based on their respective shadow wages and per unit labour hours expended in order to procure the respective energy sources. Ordinary Least Squares and Tobit models were used to estimate household demand for fuelwood, and for charcoal and agricultural fuels, respectively. A dynamic long-term model of the energy sector in Ethiopia was used to investigate the development of renewable energy for cost-effective energy diversification. Finally, the suitability of institutional arrangements and collective action for increased decentralized energy generation among remote communities were also evaluated.

The regression results show that fuelwood scarcity or a decrease in the shadow wage of fuelwood collection labour was negatively associated with the allocation of labour to agriculture, and per capita energy and food expenditures. Greater shadow wages for agricultural activities had negative relationships with the allocation of labour to fuelwood collection. Fuelwood scarcity was positively associated with labour allocation to fuelwood collection. The allocation of labour to fuelwood collection had a negative self-reward effect with an increase in shortage of fuelwood. Increases in the opportunity cost of fuelwood collection were associated negatively with the use of this fuel type, with an own-price elasticity value of –0.38. These results suggest that fuelwood scarcity has negative effects on household welfare.

Agricultural fuels and kerosene were not substitutes for fuelwood, which conforms to the results of previous studies. The relationships between biomass use and household wealth, access to electricity, and population density were consistent with theoretical expectations. Household energy use in Ethiopia appears to conform to the 'energy stacking' or ‘multiple fuel utilization' concept. However, access to modern forms of energy and economic growth played central roles in such a transition. Concerted policies are needed to help improve living standards and entrepreneurial skills among rural households.

Furthermore, the model results indicate that hydroelectric power will dominate the country’s energy mix without intervention with respect to technological progress and efficiency innovations. Over the long term, however, it is predicted that droughts will adversely affect the reliability of this energy source and the cost of energy will increase as a result. To cope with the expected effects of drought on hydroelectric power generation, the country needs to invest more in alternative renewable energy resources. In terms of energy security this would improve both sustainability and resilience, but also increase production costs. Innovations that improve the technology and efficiency of alternative energy sources, especially solar energy, would increase energy resource diversity and reduce production costs, shadow prices, and resource scarcity. Such innovations are therefore key for mitigating the expected effects of drought and improving energy security, and thus would likely serve as an engine of economic growth.

The results of a cost-benefit analysis for the development of biogas in Ethiopia suggest that subsidies for large decentralized biogas plants could achieve greater profits than smaller household biogas plants. Specific policy measures should improve energy efficiency, substitution, and technical performance; provide tangible incentives such as capital subsidies and feed-in tariffs; and ensure the availability of microcredit for the development of renewable energy and include rural households in local ‘smart grid’ power generation projects.

Bio-basierte Energie, ländliche Existenzgrundlagen und Energiesicherheit in Äthiopien

Zusammenfassung

Der Energiekonsum in Äthiopien basiert überwiegend (zu 90%) auf der traditionellen Nutzung von Biomasse für häusliche Bedürfnisse, meist für den Betrieb rudimentärer Kochöfen. Vor diesem Hintergrund untersucht die vorliegende Arbeit die Bedeutung von Biomasse für die Energienutzung ländlicher Haushalte und analysiert die langfristige Energiesicherheit. Zu diesem Zweck wird ein Farmhaushaltsmodell entwickelt, um den Zusammenhang zwischen Biomassenutzung zur Energiegewinnung und Nahrungssicherheit zu untersuchen. Die Studie erforscht die Effekte von Feuerholzknappheit auf die Lebensgrundlage der Menschen durch eine Untersuchung der Entscheidungen von Haushalten über den Einsatz von Arbeitskraft sowie Ausgaben für Nahrung und Energie. Für diese Untersuchungen wird ein Paneldatensatz äthiopischer Haushalte genutzt: Aufgrund der Endogenität von Schattenpreisen und um Selektionsfehler zu vermindern wird ein zweistufiges Kleinste-Quadrate-Modell mit fixen Effekten und eine inverse „Mills-Ratio“ für Löhne sowie Nahrungs- und Energieausgaben genutzt. Zudem wird eine „scheinbar unverbundene Regressionsanalyse“ („Seemingly Unrelated Regression analysis“) und ein fast-ideales Nachfragesystem („Almost Ideal Demand System“) genutzt, um die Arbeitsallokation und den Anteil der Arbeit der drei genannten Aktivitäten gleichzeitig zu schätzen. Diskrete Haushalts Energie-Entscheidungen werden mit Hilfe eines multinomialen Logit-Modells mit vorhergesagten Löhnen und anderen Bestimmungsfaktoren geschätzt. Schattenpreise von Feuerholz und landwirtschaftlichen Brennstoffen werden anhand ihrer jeweiligen Schattenlöhne und der Arbeitszeit, die aufgewendet werden muss, um die jeweiligen Brennstoffe zu beschaffen, geschätzt. Weiterhin wird ein Kleinste-Quadrate- und Tobit Modell genutzt, um die Haushaltsnachfrage nach Feuerholz, Holzkohle und landwirtschaftlichen Brennstoffen zu schätzen. Ein dynamisches langfristiges Modell für den Energiesektor in Äthiopien wird genutzt, um die Entwicklung der kostengünstigsten Quelle von erneuerbarer Energie für eine kosteneffektive Energiediversifizierung auf nationaler Ebene zu untersuchen. Schließlich werden institutionelle Veränderungen und kollektives Handeln hinsichtlich ihrer Nützlichkeit für dezentrale Energieerzeugung für abgelegene Gemeinschaften evaluiert.

Die Regressionsergebnisse zeigen, dass Feuerholzknappheit oder eine Abnahme des Schattenlohns für das Sammeln von Feuerholz negative Effekte auf die Allokation von Arbeit auf die Landwirtschaft, Energie- und pro-Kopf-Ausgaben haben. Gleichzeitig haben höhere Löhne in der Landwirtschaft negative Effekte auf die Allokation von Arbeit auf das Sammeln von Feuerholz. Die Allokation von Arbeit auf das Sammeln von Feuerholz hat einen negativen Eigen-Lohn-Effekt. Eine größere Knappheit von Feuerholz ist assoziiert mit dem Kauf von Energie, die auf Biomasse basiert. Ein Anstieg der Opportunitätskosten von Feuerholz ist mit einem Rückgang der Nutzung dieses Brennstoffs mit einer Eigenpreiselastizität von –0,38 verbunden. Dies legt nahe, dass Feuerholzknappheit negative Effekte auf das Wohlbefinden von Haushalten hat.

Landwirtschaftliche Brennstoffe und Kerosin sind keine Substitute für Feuerholz, was Ergebnissen früherer Studien entspricht. Der Wohlstand von Haushalten, Zugang zu Elektrizität, Bevölkerungsdichte haben den erwarteten Effekt auf die Nutzung von Biomasse. Die Energienutzung von Haushalten entspricht dem Konzept des ‚energy stacking‘ bzw. der ‚multiplen Brennstoffnutzung‘. Zugang zu modernen Formen von Energie und wirtschaftliches Wachstum spielen jedoch eine zentrale Rolle bei einer solchen Transition. Gezielte politische Maßnahmen sind notwendig, die ländlichen Haushalten helfen, ihren Lebensstandard und die unternehmerischen Fähigkeiten von Haushalten zu verbessern.

Weiterhin zeigen die Modellergebnisse, dass ohne Interventionen in technologischen Fortschritt und Innovationen zur Effizienzverbesserung hydro-elektrisch erzeugte Energie den Energiemix des Landes dominieren wird. Langfristig wird jedoch vorausgesagt, dass Dürren die Zuverlässigkeit dieser Energiequelle beeinträchtigen und die Kosten für die Energiegewinnung in die Höhe treiben werden. Um

diese Einflüsse von Dürren auf den hydro-elektrischen Sektor in Äthiopien zu bewältigen, muss Äthiopien mehr in die Entwicklung erneuerbarer Energieressourcen investieren. Dies würde sowohl die Nachhaltigkeit als auch die Resilienz verbessern, aber auch die Produktionskosten erhöhen. Innovationen für eine Verbesserung der Technologie und der Effizienz der Gewinnung alternativen Energien, vor allem Solarenergie, erhöhen die Diversität der Energiequellen und reduzieren Produktionskosten, Schattenpreise und Ressourcenknappheit. Solche Innovationen sind deshalb zentral für eine Reduktion der Risiken durch Dürren und um die Energiesicherheit zu verbessern.

Die Ergebnisse einer Kosten-Nutzen-Analyse für die Entwicklung von Biogas deuten darauf hin, dass Subventionen for große dezentralisierte Biogasanlagen höhere Gewinne erzielen könnten als kleine Biogasanlagen für Haushalte. Konkrete Politikmaßnahmen sollten Energieeffizienz- und substitution und die technische Leistungsfähigkeit verbessern, spürbare Anreize wie z.B. Kapitalsubventionen und Einspeisevergütungen setzen, die Verfügbarkeit von Mikrokrediten für die Entwicklung von erneuerbaren Energien sicherstellen sowie ländliche Haushalte in lokale ‚intelligente Stromnetze‘ einbeziehen.

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Acknowledgments

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Abbreviations

AHM	Agricultural Household Model
AIDS	Almost Ideal Demand System
asl	Above sea level
Btu	British thermal unit
BU	Bottom up
CDM	Clean development mechanism
CGE	Computable general equilibrium
CHP	Combined heat and power
CIA	Central Intelligence Agency
CO_2	Carbon dioxide
CRGE	Climate resilient green economy
CSA	Central Statistical Agency
CSAE	Centre for Studies of African Economies
CSP	Concentrated solar power
DREI	Decentralized renewable energy investment
EC	European Commission
EEA	Ethiopian Economic Association
EEA	European Environment Agency
EEPCO	Ethiopian Electric Power Corporation
EIA	Energy Information Administration
EIA	Ethiopian Investment Agency
EKC	Environmental Kuznet's curve
EPA	Environment Protection Authority
EPE	Ethiopian Petroleum Enterprise
IFPRI	International Food Policy Research Institute
EPE	Ethiopian Petroleum Enterprise
EREPDC	Ethiopian Rural Energy Development and Promotion Centre
ERHS	Ethiopian Rural Household Survey
ETB	Ethiopian Birr
EWEA	European Wind Energy Association
ESMAP	Energy Sector Management Assistance Programme

FAO	Food and Agriculture Organization of the United Nations
FRA	Forest Resource Assessment
GAMS	General algebraic modelling system
GDP	Gross domestic product
GHG	Greenhouse gas
GMI	Global Methanol Initiative
GEARV	Great East African Rift Valley
GERD	Grand Renaissance Dam
GTP	Growth and transformation plan
GTZ	German Society for International Cooperation
GW	Gigawatts
GWh	Gigawatt hours
HH	Household
ha	Hectares
IAP	Indoor air pollution
ICS	Interconnected system
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISO	International Sugar Organization
FE-2SLS	Fixed Effect Two-Stage Least Squares
KBBE	Knowledge-based bioeconomy
kg	Kilogram
km	Kilometre
km^2	Square kilometre
kWh	Kilowatt hours
LFG	Landfill gas
LCC	Life cycle cost
LCoE	Levelized Cost of Energy
LP	Linear programing
t	Metric tonnes
TD	Top down
m	Metre
m^2	Square metre

m^3	Cubic metre
MDGs	Millennium Development Goals
MoFED	Ministry of Finance and Economic Development
MoWE	Ministry of Water and Energy
MW	Megawatts
MWh	Megawatt hours
MPWSE	Master Plan of Wind and Solar Energy
NBPE	National Biogas Programme of Ethiopia
NEA	National Energy Agency
NGO	Nongovernmental organization
NIE	New Institutional Economics
NREL	National Renewable Energy Laboratory
OLS	Ordinary Least Squares
PEDN	Poverty-environmental degradation nexus
PFM	Participatory forest management
PV	Photovoltaic
REDD	Reducing emissions from deforestation and forest degradation
SC	Self-constrained system
SNNPR	Southern Nations, Nationalities, and Peoples' Region
SNV	Stichting Nederlandse Vrijwilligers
TJ	Terajoule
TWh	Terawatt hours
UEAP	Universal Energy Access Programme
UK	United Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Organization for Education, Science, and Culture
USA	United States of America
US$	United States dollar
US EPA	United States Environmental Protection Agency
WBISPP	Woody Biomass Inventory and Strategic Planning Project
WB	World Bank

WEF	Water-energy-food nexus
WHO	World Health Organization

Chapter One

Introduction

1.1. Background

1.1.1. Energy and sustainable development

Modern forms of energy play an enabling role in sustainable development and are closely linked with poverty reduction, climate change mitigation, education, food security, and public health (ESMAP, 2003; Cabraal et al., 2005; Rehfuess et al., 2005; Gaillard, 2008; Kaygusuz, 2011; Thiam, 2011; Bazilian et al., 2012; Karekezi et al., 2012; Mainali et al., 2014). There are two common forms of energy use: for survival or subsistence purposes and for development (EEA, 2009; Karekezi et al., 2012). Subsistence energy use includes energy use for everyday livelihood activities, occurring since ancient times when our ancestors used fire for cooking food they had gathered or hunted. In the modern era this also includes a wide range of activities such as heating and illuminating homes, and operating equipment such as radios, refrigerators, televisions, computers, and cellular phones. Subsistence energy use is related to household living standards; social, economic, health, and educational status; and improvements to it contribute to the quality of life. Development energy use is a necessary input for the production of goods and services, typically in the tertiary industrial, commercial, service, and transportation sectors. In this sense energy is the lifeblood of modernization, as it is vital in every aspect of human political, social, and economic development, and for environmental protection. Differences in the quality and quantity of energy use are considered important indicators of the disparities between poor and wealthy countries or households. In general, without access to reliable, affordable, and clean energy it is impractical to address extreme poverty and pursue sustainable development goals.

The issue of future energy security has gained increasing attention worldwide. Energy security implies sustainable supply; acceptable sources, costs, and price stability; continued or improved accessibility; and avoiding threats to public safety or health and the environment (Kruyt et al., 2009). Recently the United States Energy Information Administration (EIA) projected global energy demand over the next three decades and predicted that it will increase from 524 quadrillion Btu in 2010 to 850 quadrillion Btu in 2040 (EIA, 2013). The EIA also estimated that over 85% of the growth in global energy demand corresponds to the developing world and is driven by rapid population and economic or gross domestic product (GDP) growth. Achieving each of the Millennium Development Goals (MDGs) is contingent upon greater access to affordable, cleaner, and modern sources of energy (Karekezi and Majoro, 2002; Modi, 2004; Porcaco and Takada, 2004; Cabraal et al., 2005; Modi et al., 2005; Karekezi et al., 2012). Energy is a vital factor in the prosperity of nations and integral to social welfare. In developing countries reliance on solid biomass energy resource use may have enduring negative impacts on the environment, living conditions, public health, gender equity, and child school attendence. To avoid these problems it is necessary to design and implement appropriate policies.

1.1.2. Biomass energy use and related challenges in developing countries

The perplexing nature of the global energy problem is reflected in the persistent overreliance on solid biomass for the subsistence energy needs of the world's poor, which is often compounded by growing fuelwood scarcity and poverty traps in developing countries. Worldwide it is estimated that 1.4 billion people lack access to electricity and that 2.7 billion, mostly in Sub-Saharan Africa and Asia, rely on traditional energy resource use (Karekezi et al., 2012; IEA, 2013). These people rely on the traditional use of biomass resources such as fuelwood, charcoal, agricultural fuels (cattle dung and crop residues), and also coal for survival purposes, typically using rudimentary and inefficient technologies. The high degree of reliance on traditional biomass energy use in developing countries is likely to continue, particularly in Sub-Saharan Africa (FAO, 2008). Deprivation of access to clean energy remains a pressing challenge, especially in off-grid areas of developing countries. Broader intervention is required to ensure greater access to modern energy services in order to meet the energy needs of the majority of the global population living in developing countries (UN, 2013).

Reliance on inefficient solid biomass energy use negatively affects public and environmental health due to exposure to indoor air pollution (IAP) and contributing to climate change. Annually about four million premature deaths are associated with IAP worldwide (WHO, 2006; Lim et al., 2012; Smith, 2012; Thurber et al., 2014). The WHO (2009) estimated that in Ethiopia about 72,400 deaths per year are attributable to IAP associated with the inefficient residential combustion of biomass energy resources. Studies indicate that open-air combustion of solid bio-based energy resources contributes to climate change through greenhouse gas (GHG) emissions associated with deforestation and forest degradation that result from the overexploitation of fuelwood (Venkataraman et al., 2005; Wang, 2009). Deforestation and forest degradation also have negative effects on precipitation patterns (Rasul, 2014), exacerbating the effects of global warming. Although insufficient attention has been given to biomass energy issues in the past, there is growing global awareness of the crosscutting problems and opportunities associated with them (GTZ, 2006). Improving the efficiency of household biomass energy use is considered a key approach for improving environmental, public health, and safety conditions in developing countries (FAO, 2006), particularly in Sub-Saharan Africa (Rehfuess et al., 2010). Ethiopia is among the few remaining countries with a high percentage (over 90%) of its population reliant on solid biomass (IEA, 2013). Developing strategies for improving the efficiency of biomass energy use requires better understanding of its contributions to energy security at household and national levels.

1.1.3. Background and the energy situation in Ethiopia

Ethiopia is home to one of the world's oldest civilizations and has many other distinctive and historical features. It is the origin of Arabica coffee and the oldest (4.4 million years old) known iconic human ancestor. Ethiopia also has distinctive biodiversity, including many endemic species. It is a land-locked country situated in the horn of East Africa in close proximity to the Middle East, western Asia, and Europe. The county has an area of 1.12 million square kilometres and an estimated population of 92 million. Despite its unique history and natural bounty, the country is among the poorest in the world, ranking 173 out of 187 countries according to the human development index of the United Nations Development Programme (UNDP, 2013). In recent history the country has suffered from chronic famine due to a combination of civil war, recurrent drought, and persistent political crises. Food insecurity is endemic to the horn of Africa due to the regular frequency of severe drought (Sasson, 2012). The perpetual food security crisis in Ethiopia is also attributed to a "complex interaction of supply, distribution, and demand factors" (von Braun and Olofinbiyi, 2007). The principal economic activity of the country is agriculture, which accounts for approximately 42% of the GDP, 80% of employment, and 70% of export earnings (MoFED, 2011). Recently, however, there are significant prospects for future growth. Ethiopia has a GDP per capita of US$ 410, which grew at an average annual rate of 10.6% over the last decade (World Bank, 2013a). The country is striving to transform its agrarian based economy with the goal of becoming an industrialized middle-income country in the next decade (CRGE, 2011).

The geographical location of Ethiopia gives it exceptional renewable energy resource potential in terms of both diversity and abundance. The Great East African Rift Valley (GEARV) dissects the country, providing considerable geothermal energy potential. The country's proximity to the equator, low humidity climate, and extensive highlands provide exceptional solar and wind power potential. The country is regarded as the water tower of Africa, with several large rivers draining its highlands. Although most of the overpopulated highlands of the country have long been denuded, some fragments of Dry Afro-montane forest, broadleaf rainforest, and coffee forest remain, making the country a good candidate for 'reducing emissions from deforestation and forest degradation' (REDD) programme efforts.

Despite these positive circumstances Ethiopia faces immense energy challenges. Approximately eight out of ten of its citizens dwell in rural areas with limited access to modern energy. Bio-based energy resources are expected to continue to dominate Ethiopia's energy mix into the foreseeable future due to high reliance on traditional biomass use and a slow rate of transition to modern forms of energy generation (Shanko, 2009).

Ethiopia is completely reliant on oil imports, which exposes it to the risk of petroleum product price increases. Electricity generation in the country is heavily reliant on hydroelectric power, which is unreliable due to increasing agricultural demand for water, the high frequency and intensity of droughts and other climatic shocks, and international conflict over water rights in Africa. The limited availability of electricity is one of the main constraints on the economy. Ethiopia has the lowest levels of electricity access and per capita consumption in the world, but has the potential to become a regional power hub. Renewable energy development is a core policy position of the federal government, therefore better understanding of cost effective energy diversification investment is vital for making informed decisions for meeting these challenges.

Despite the country's progressive energy policy focus on renewables, the ubiquity of traditional biomass use remains a pressing challenge. This reliance on improperly managed traditional biomass use has resulted in the overexploitation and significant depletion of Ethiopia's forest resources, with annual forest cover loss estimated at 140,000-200,000 ha (Jargstorf, 2004; FAO, 2010a). This has resulted in fuelwood scarcity, especially in overpopulated highland areas. In turn, this impinges on household livelihoods in a variety of ways. In the face of fuelwood scarcity households meet their survival energy requirements by substituting agricultural fuels (cattle dung and/or crop residues) for fuelwood. This in turn contributes to the reduction of soil fertility and annual agricultural yield losses of about 7% (Gebreegzihabiher, 2007).

There is little empirical-based understanding, however, of how rural livelihoods are impacted by these problems and what policy innovations are required to mitigate such impacts. In order to accelerate the transition towards sustainable energy, Ethiopia could invest in improving solid biomass energy use efficiency and its renewable energy potential. The sustainability of biomass energy use and particularly efficiency can and should be improved in ways that contribute to modern energy development.

1.1.4. Fuelwood scarcity, household energy use, and related welfare effects

Resource scarcity remains an underlying cause of global and local economic and environmental crises causing disequilibrium between local and global demand and supply, and volatility in resource prices (Lopez, 2012; Delay, 2013). It has long been recognized that poverty and environmental degradation or deforestation are often highly correlated, particularly in poor tropical countries (Angelsen and Kaimowitz, 1999). Resource scarcity (e.g. land, water, forest) is becoming an increasingly important challenge to sustainable development (environmental, social and economic) and closely related to poverty in developing countries, but the exact nature of the relationship is contested and is often described as ‘closely related’ or ‘co-located’ (Lee, 2011; Delay, 2013).

Rapidly growing populations and widespread land constraints have contributed to intensified deforestation in many developing countries. Due to the high rate of deforestation in many parts of Ethiopia the demand for fuelwood has already exceeded local supply and led to fuelwood scarcity (Jargstorf, 2004). Rural populations require energy for their survival on a daily basis, however, and the drastic loss of forest cover and fuelwood scarcity infringe on the livelihoods of the poor in a variety of ways.

Deforestation has negative consequences on the environment such as biodiversity loss, soil erosion, ecosystem degradation, global warming, etc. The nature of the relationships between poverty and environmental degradation is not clearly understood. Some studies have found that dependence on fuelwood is strongly linked to poverty (Heltberg et al., 2000; Démurger and Founier, 2011). Other studies have found that increases in household assets and income are associated with increased fuelwood use (Mekonnen, 1999; Shi et al., 2009). Sapkota and Oden (2008) found that among Nepalese households the poor were highly dependent on fuelwood. In contrast, Shaheen and Shahrukh (2009) found no evidence of an ‘environmental poverty nexus’ in Pakistan, as poor and higher income households were equally dependent on forest resources, thus resource degradation is not necessarily driven by poverty alone. A study that analysed data from the ‘Demographic and Health Survey’ in Benin, Kenya, and Ethiopia found that household fuel choice in these countries is more ‘supply driven’ than ‘demand driven’ (Rehfuess et al., 2010). That study suggested that in order to promote household ‘fuel-switching,’ policy efforts should consider supply-side limitations. Fuelwood scarcity appears to be the main supply side constraint that affects household livelihoods through increasing the labour requirements of fuelwood collection.

Many studies have investigated the determinants of household energy choice and how fuelwood scarcity affects energy substitution decisions and household welfare in other countries. Typically, households increase the amount of labour allocated to fuelwood collection in response to increased fuelwood scarcity (Cooke, 1998; Johnsen, 1999; Heltberg et al., 2000; Palmer and Macgregor, 2009; Bandyopadhyay et al., 2011; Damte et al., 2012). Households are often forced to modify cooking habits and dietary diversity due to increasing labour requirements for fuelwood collection (Brouwer et al., 1997). Fuelwood scarcity often results in greater malnutrition among children due to the lack of fuel to cook food, which not only forces households to switch to foods that can be more easily cooked, but also increases fuelwood collection efforts among women and thus reduces the time available for cooking.

There are also welfare effects attributed to the use of agricultural residues for energy as opposed to the enhancement of soil fertility. In the face of fuelwood scarcity households are expected to use substitute or complementary alternatives. Although household fuel substitution has been studied extensively there is lack of consensus regarding the substitutability of agricultural fuels for fuelwood. Some studies have found that extreme fuelwood scarcity leads households to substitute agricultural fuels for fuelwood (Van‘t Veld et al., 2006; Agarwal, 2010). Other studies have found limited evidence of substitution between fuelwood and lower quality agricultural fuels such as cattle dung and crop residues (Mekonnen, 1999; Palmer and Macgregor, 2009; Damte et al., 2012). Households may switch to commercial energy alternatives if they are available (Hyde and Köhlin, 2000; Chen et al., 2006; Guta, 2012a; Lee, 2013). Rural households may cope with fuelwood scarcity by shifting from the use of communal forests to private tree cultivation (Van‘t Veld et al., 2006; Gebreegzihabiher, 2007).

Fuelwood scarcity often has greater impacts on the welfare of women and children because in most of the developing world they are traditionally responsible for fuelwood collection (Heltberg, 2004; Rehfuess et al., 2010). Relative to men, women and children also suffer substantially higher rates of illness and mortality arising from exposure to IAP from unventilated biomass stoves because of gender inequities related to cooking responsibilities (Rehfuess et al., 2005; Agarwal, 2010). In rural Ethiopia women and children are also the primary agricultural labourers, which means that fuelwood scarcity can lead to competition for agricultural labour, thus creating a fuel-food trade-off.

One review of studies on household energy use in developing countries found that the effects of determinants of household energy demand are unclear (Lewis and Pattanayak, 2012). There is also scant empirical understanding of the effects of fuelwood scarcity on household welfare in terms of fuel-food trade-offs, energy expenditures, fuel choice, household bio-based energy use, and household energy substitution. Though studies have investigated household mechanisms for coping with fuelwood scarcity (Damte et al., 2012), there is no quantitative empirical evidence of the impacts of fuelwood scarcity on household agricultural labour and resulting welfare effects. This study used an Agricultural Household Model (AHM) to investigate the impacts of fuelwood scarcity on household bio-based energy use, energy expenditures, fuel choice, and welfare implications. The model also enabled the examination of Ethiopia's rural energy challenges and the effects of fuelwood scarcity on agricultural production and food security.

The negative livelihood impacts of fuelwood scarcity and ways to mitigate them have barely been explored. Moreover, most studies have been limited to analyses of household energy expenditures and often use the World Bank's Living Standards Measurement Study that was designed for other purposes and that lacks detailed information on energy consumption. The lack of data on household bio-based energy use has constrained analyses of the welfare effects of energy and environmental resource scarcity on livelihoods and fuel-switching or energy substitution. Empirical analysis of the impacts of deforestation or fuelwood scarcity reflected in changes in the shadow cost of fuelwood collection on household welfare and energy substitution can yield results that support formulating policy to hasten rural energy transition and sustainable development. Many studies from Ethiopia are based on cross-sectional surveys, which, with the exception of Mekonnen and Köhlin (2008) and Guta (2012a), cannot account for temporal factors related to rural energy use. The use of panel survey enabled this study to control for unobserved individual heterogeneity and to capture temporal effects of household labour allocation. However, the lack of information on household biomass energy use in the initial survey limited the scope of the analyses.

1.1.5. The nexus of water, energy, and food

The trade-off and welfare effects should be explored within the lens of the broader water-energy-food nexus; a concept that has evolved recently and has been receiving growing scientific attention. The fundamental policy challenge of water, energy, and food security goes beyond simple fuel-food trade-off considerations to a broader conceptual understanding of the linkages among these essential components of human welfare (Hoff, 2011), ecosystem function (Rasul, 2014), and land use (Ringler et al., 2014). The welfare effects of fuelwood scarcity or fuel-food trade-offs are part and parcel of the water-energy-food nexus concept.

Recently the world has been experiencing significant increases in demand for water, energy, and food. International events such as the Bonn Nexus conference in 2011 highlight the growing interest in the interdependency of the components of the water-energy-food nexus (Hoff, 2011). In the literature and policy debate there has been little attention to how the water-energy-food nexus affects prices (Gulati et al., 2013). Sustainable development implies consistent availability of safe water, energy, food, and industrial resources on a renewable basis (von Braun, 2013). Agricultural and energy policies are interrelated with water constraints (Hermann et al., 2012). Energy is considered a key input in agriculture intensification for activities such as pumping irrigation water; fertilizer production; post-harvest processing, packaging, and transport; and bioenergy treatment and processing (Ringler et al., 2014). Decreasing water availability combined with climate change and increasing water demand for energy and agricultural production pose significant challenges.

The water-energy-food security nexus involves complex interdependencies that have important implications for managing trade-offs and promoting synergies surrounding them, sustainable development, ecosystem function, land use, and climate change (Hermann et al., 2012; Hussey and Pittock, 2012; Gulati et al., 2013; Rasul, 2014). The complexity of the nexus is attributed to large knowledge gaps about the interactions, feedback mechanisms, and adaptive options across economic sectors (Hoff, 2011). The nexus concept recognizes this interconnectedness to facilitate the development of joint solutions for mitigating trade-offs and promoting synergies for sustainable development (Hoff, 2011; von Braun, 2013; Ringler et al., 2014). An integrated approach is needed for the management and productive use of energy, land, and water resources (Popp et al., 2014).

In this sense the nexus concept is extremely important for Sub-Saharan Africa (Hermann et al., 2012; Gulati et al., 2013) and for Ethiopia in particular. This is because the region faces daunting water, energy, and food security problems. Water scarcity has important implications for Ethiopia's energy and food security (EEA, 2009; Sesson, 2012), and there is evidence that power rationing has constrained its economic growth (Engida et al., 2011).

Ethiopia's Climate Resilient Green Economy (CRGE) and energy policy should be considered within the context of the nexus concept framework. Water and land resources are critical inputs for food and energy production. Although in this study could not explicitly model water use trade-offs between agricultural and energy production, I analysed the use of water for energy generation using a national-level energy sector model for Ethiopia. The model also considered energy security by simulating the potential impacts of drought on water availability for power generation. The use of marginal agricultural land for agro-forestry and existing forest cover were incorporated into the model as biomass supply parameters for meeting solid biomass energy demand and electricity generation. More precisely, the study examined biomass energy use at both household and national scales. It also investigated how technical innovation and increased efficiency could reduce reliance on solid biomass energy and drought vulnerable hydroelectric power generation, and promote energy security. The use of agricultural biomass waste for either energy or improving soil fertility represents a fuel-food trade-off. Bio-based energy is a central component of the broader 'bioeconomy' concept that has evolved recently as an integrated approach for the efficient use of diverse biomass resources such as forest-based biomass, agricultural and industrial waste, and solid residential waste for the production of modern energy and high value organic products.

1.1.6. The bioeconomy concept

In recent policy debates the advantages of shifting from a fossil fuel based economy towards a bio-based energy economy have received increasing attention (Langeveld et al., 2010; Vandermeulen et al., 2011). The bioeconomy concept is an integrated approach to sustainable bio-based resource use for a variety of economic and social needs. The German government's bioeconomy council defined it as "the knowledge-based production and use of biological resources to provide products, processes and services in all economic sectors within the frame of a sustainable economic system" (Bioeconomy Council, 2013). In this sense it is an "economy where the basic building blocks for materials, chemicals and energy are derived from renewable biological resources" (McCormick and Kautto, 2013). The bioeconomy concept encompasses a broad spectrum of economic sectors, including not only agriculture, but also fisheries, aquaculture, algae cultivation, forestry, and waste management industries (European Commission, 2007; 2012: McCormick and Kautto, 2013: von Braun, 2013). The socio-economic implications of the bioeconomy concept can be measured in terms of economic indices such as employment and economic gains, energy, and food security (Domac et al., 2005; Chin et al., 2013). The fulfilment of the bioeconomy concept offers opportunities for the establishment of bio-refineries and organic-based industries in rural areas where biomass feedstock is produced, providing an advantage to poor farmers (Domac et al., 2005; von Braun, 2013).

There are complex threats to the environmental sustainability of crop diversity, land and water resources, conservation areas, and food security (Hill et al., 2006; von Braun, 2007; FAO, 2013). These problems are related to a number of social, cultural, institutional, and environmental issues (Domac et al., 2005; Chin et al., 2013). There are several benefits, risks, and uncertainty associated with bioeconomy development (Langeveld et al., 2010). Evidence based empirical studies are required to help countries develop effective strategies for mitigating risks and to promote the benefits of a bioeconomy, especially for poor households in developing countries. The design of appropriate policy tools for the development of a bioeconomy, however, is not an easy task because of the many different actors involved (Vandermeulen et al., 2011). Technological innovation is a key counterpart to appropriate policies by providing the necessary impetus for strategies that enable countries to develop bioeconomies and reduce associated risks (von Braun, 2013). There is limited knowledge of the bioeconomy concept as it applies to Ethiopia with respect to bio-based energy utilization and food security links.

1.2. Research problem

Like many other developing countries Ethiopia is faced with critical energy access and supply problems for its largely rural economy. The chronic and deepening lack of energy access in rural areas undermines economic development and poverty alleviation efforts. Continued reliance on traditional bio-based energy has numerous negative environmental and public welfare consequences, such as biodiversity loss, soil erosion, health risks, and threatened livelihoods. The lack of modern energy infrastructure, technological constraints, the scattered distribution of rural settlements, various socio-behavioural and institutional obstacles, and numerous supply and demand constraints have inhibited access to clean energy, particularly in remote areas. The country faces a growing power demand and supply gap, and even in urban centres power outages and interruptions occur on a regular basis. Empirical studies on household energy use in Ethiopia have focused on both urban household fuel choice and improved efficiency stove adoption (Kebede et al., 2002; Mekonnen and Köhlin, 2009; Gebreegziabher et al., 2012; Alem et al., 2013), and rural household energy use (Mekonnen and Köhlin, 2008; Damte et al., 2012; Guta, 2012a). However, analyses of the effects of deforestation or fuelwood scarcity on household welfare and policy interventions required to avert the problem are needed for Ethiopia.

Improvement in biomass energy use efficiency and modernization for cleaner energy generation at both the community and national scales are expected to contribute to multiple objectives. Modern forms of bio-based energy, which is intertwined with rural livelihoods and the mainstay of the national energy system in Ethiopia, are a central component of the triple sustainable development criteria (i.e. social, economic and environmental), agricultural transformation, and poverty alleviation. Ubiquitous overreliance on traditional and inefficient use of biomass resources by destitute rural Ethiopian households provided the impetus to study the linkages between bio-based energy use and household livelihoods.

There are several shortcomings in the existing literature on this subject. First, there are limited empirical studies that have explicitly investigated the linkages among fuelwood, agriculture activities, and off-farm employment. Second, there has only been limited exploration of the effects of the shadow wages of fuelwood, agricultural activities, and off-farm employment on household inter-fuel substitution or fuel choice and household energy expenditure patterns. Third, there have not been any efforts to examine the effects of energy intervention policies (i.e. rural electrification and improved efficiency biomass stove use) on household energy use in rural Ethiopia. This study provided an in-depth analysis of household bio-based energy use that enables greater understanding of the potential strategies for improving household energy use efficiency and promoting energy substitution at both household and national scales.

Broader policy challenges of the rural energy problem go far beyond household fuel choice and stove adoption, making it necessary to investigate its linkages with agriculture and livelihoods. Integrated approaches should seek to address the inefficiency of traditional residential biomass energy utilization and hasten the transition to improved methods of energy use. Most studies have overlooked the fact that households often produce food and bio-based energy jointly, and that labour opportunity costs affect household livelihoods. Bio-based energy is intrinsically linked to food security and rural livelihoods in multifaceted ways. This is reflected in the consequences of fuelwood scarcity on household wellbeing, including fuel-food trade-offs, health aspects, gender inequity, and various socio-economic and environmental sustainability issues. There has been limited empirical evidence about the potential contributions of more efficient bio-based energy use to household livelihoods and national energy security.

Growing energy demand triggered by economic and population growth is putting the energy sector under pressure (EEA, 2009). There are few existing models of Ethiopia’s energy sector for considering electricity production and sustainable bio-based energy use. Energy sector models can help policy makers contemplate the optimal investment path for sustainable energy development. Biomass remains a key strategic option for Ethiopia’s long-term energy security. Thus, empirical study is required to examine ways of improving the efficiency of bio-based energy use at the grass-roots level and to explore strategies for modern biomass energy development.

1.3. Research objectives, questions and hypothesis

This study examines household bio-based energy utilization and associated linkages to rural livelihoods, and the potential contribution of sustainable and more efficient biomass use and other renewable energy for Ethiopia’s future energy security. The overall goal of this study was to explore strategies for developing and modernizing biomass energy use and other renewable energy options that generate opportunities for sustainable development, poverty reduction, and environmentally responsible growth. Better understanding of these issues is expected to benefit policy efforts to improve living standards, especially the energy deprived rural poor and marginalized women and children. This study contributes coherent evidence to related literature by paying special attention to agricultural household energy use by assessing the role of bio-based energy on rural livelihoods and by filling research gaps and shortcomings. This study also endeavoured to achieve a better understanding of the bottlenecks, barriers, and opportunities associated with community-based decentralized energy use, and how such efforts can improve energy access problems in remote communities.

The main research hypothesis is that households will respond to increasing fuelwood scarcity by changing labour allocation, changing fuel choices and expenditures on commercial fuels and food, adopting improved efficiency biomass stove technology, and/or energy substitution. Therefore intervention in rural energy supply and improvement in the efficiency of residential bio-based energy use are expected to improve rural livelihoods and contribute to the energy security of the country. Fuelwood scarcity or fuelwood shadow wage decline is likely to motivate households to reduce the amount of labour allocated to agriculture or food production. Thus, increased access to fuelwood (forest) would result in increased shadow wages for fuelwood associated with corresponding increases in labour time allocated to agricultural activities. Investment in more sustainable and efficient renewable energy use should enhance Ethiopia's energy security and economic growth. Advancements in technological innovation and efficiency or adaptability should contribute to energy security. Livelihood diversification through greater engagement in off-farm and self-employment opportunities is expected to reduce environmental pressure associated with traditional biomass energy use. Greater access to clean energy is expected to reduce household need for traditional biomass energy and thus improve welfare. Specifically, the study addressed the following objectives:

1. To analyse rural Ethiopian household bio-based energy utilization behaviour in order to better understand the related linkages to food security.
2. To investigate the potential contributions of lower cost, more sustainable, and more efficient renewable energy resource (particularly biomass) use options to energy security in Ethiopia.
3. To assess the role of institutional arrangements, strategies, and collective action for enhanced decentralized renewable energy use in remote areas of the country.

The study addressed the following research questions:

1. (a) What is the nature of the linkages (competition or complementarity) between bio-based energy utilization and food security or rural livelihoods in Ethiopia?
   (b) What are the effects of fuelwood scarcity (decline in the shadow wage of fuelwood collection labour time), and increases in the fuelwood collection shadow wage on labour allocation to agriculture and off-farm employment on household energy expenditures and fuel choice?
   (c) What is the effect of biomass scarcity (increase in shadow price) on household biomass energy use?
   (d) What are the roles of improved efficiency biomass use stoves and household access to electricity on bio-based energy use and energy substitution?
2. (a) What are the least cost energy resource use options for Ethiopia?
   (b) What are the roles of technical innovation and more efficient bio-based energy use for enhancing the energy security of the country?
3. (a) What are the bottlenecks and opportunities for implementing decentralized renewable energy use in remote areas of Ethiopia?

(b) What institutional structures, strategies and collective actions are required to implement a decentralized energy development strategy for rural Ethiopia?

1.4. Conceptual and theoretical background

There are two main conceptual approaches used to analyse household energy demand. The 'energy ladder' (Leach and Mearns, 1988; Munasinghe and Meier, 1993; Barnes and Floor, 1996; Lee, 2013) concept views household fuel choices as a progression that corresponds to increases in income along a hierarchical order from 'inferior' traditional biomass energy resources to transitional fuels and eventually 'superior' modern commercial fuels. The energy ladder approach perceives a continuous monotonic fuel substitution process as income increases (van Beukering, 2009). Accordingly energy resources exist along a value continuum based on cost, cleanliness, convenience, and other considerations (van der Kroon et al., 2013). The energy ladder concept has been disputed by a growing number of studies (Leach, 1992; Masera et al., 2000; Kammen and Lew, 2005; Hiemstra-van der Horst and Hovorka, 2008). For instance, fuelwood, which is considered near the bottom of the energy ladder due to its relative inconvenience and high emission levels, is not necessarily the cheapest energy option (Kammen and Lew, 2005).

Alternatively, many recent studies have conceptualized household energy choice from a perspective of 'fuel stacking' or 'multiple fuel use' (Masera et al., 2000; ESMAP, 2003; Heltberg, 2004, 2005; Schlag and Zuzarte, 2008; Mekonnen and Köhlin, 2009; Guta, 2012a). The fuel-stacking concept predicts that households will combine different energy sources for different end-uses; and that fuel choices are not mutually exclusive because households can use any combination of fuels at given point in time. The fuel-stacking concept asserts that, in addition to income, there are numerous factors that determine household fuel choice decisions.

Both the energy-ladder and fuel-stacking concepts emphasize consumer demand theory and are complementary rather than substitute approaches. They both focus on narrow aspects of residential energy choice. In practice there is little evidence of energy transition and many rural households in developing countries often depend on multiple energy sources (Heltberg, 2000; 2005: ESMAP, 2003). The relative importance of fuel stacking (multiple fuel use) and fuel-switching has not been well established (Heltberg, 2005). Some studies appear biased in favour of switching from traditional biomass energy resources to modern fuel alternatives. Studies have also underlined the roles of public infrastructure, education, and various policy tools that help households to 'leapfrog up' the energy ladder (Heltberg, 2004; Lee, 2013). However, in remote areas of developing countries energy transition is typically constrained due to an intricate web of factors and conditioned by the availability of modern energy resources (Guta, 2012a). Even in urban areas where modern forms of energy are available households may prefer to use biomass, particularly for cooking (Heltberg, 2004; Mekonnen and Köhlin, 2009).

Some recent studies have argued for increased utilization of biomass energy for the production of modern forms of energy rather than switching to climate polluting and relatively expensive fossil fuels (Prasertsana and Sajjakulnukit, 2005; Buragohain et al., 2009; Iakovou et al., 2010; Kaygusuz, 2010; Zheng et al., 2010; Niu et al., 2014). These studies have proposed an integrated rural energy transition for improving the efficiency of traditional biomass sources and the development of renewable alternatives (Niu et al., 2014). Biomass energy, and particularly fuelwood, has been the only available fuel option in many rural areas of developing countries (Arnold et al., 2003; Kaygusuz, 2010). This is particularly important in Sub-Saharan African countries because most rural households suffer from extreme poverty, a lack of access to electricity, and are unable to afford modern commercial energy alternatives, and therefore must depend on harvestable bio-based energy resources to support their livelihoods. There is also renewed interest in bio-based energy due to the negative environmental impacts of fossil fuels and their linkages with climate change and food security.

Bio-based energy is also considered a strategic substitute for fossil fuel for the reduction of GHG emissions (Iakovou et al., 2010). Renewable biomass energy has great potential for meeting energy needs in both industrialized and developing countries (Demirbas et al., 2009). In some industrialized countries bio-based energy (particularly fuelwood) has become increasingly competitive and desirable based on environmental and economic considerations (Becker et al., 2010 [USA]; Couture et al., 2010 [France]; Huttunen, 2012 [Finland]). There have been few research efforts on the trade-offs between bio-based energy and food production, or on how government policies that promote off-farm employment, improved access to modern energy, and technological advances impact those trade-offs. It has been suggested that, aside from labour allocation to fuelwood collection and agriculture, there are a variety of household coping mechanisms for dealing with biomass scarcity that deserve study (Bandyopadhyay et al., 2011).

The conceptual framework of this study depicted in Figure 1.1, which illustrates how household livelihoods are linked to the water-energy-food nexus. Decentralized energy, energy diversification, technical capability, local skills, and efficiency improvement all influence household livelihoods. Economic resources such as labour, land, capital, and water are required to produce food, energy and biomass. There are numerous external factors that determine the dynamics of the nexus such as public investment in infrastructure, energy, agriculture, technical capability building, etc. Such policies affect the prices of food, energy, and water that in turn affect the welfare of the poor. In this context policies such as providing incentives (taxes and subsidies), education, and skills training also enable households, as well as individuals and communities, to improve their technological conditions (improved agricultural practices, adoption of biogas digesters or improved efficiency biomass stoves, etc.) in which decentralized energy development can have a crucial role. This is expected to improve rural livelihoods, contribute to promoting synergies among distinct elements of the water-energy-food nexus, and mitigate risks. Hence, the household is the basic unit of analysis in the described framework.

The impacts of fuelwood scarcity on household welfare were evaluated by empirically investigating three important issues. First, the impact of fuelwood scarcity on household labour allocation to livelihood activities was examined to determine whether environmental degradation increases the labour opportunity costs of the extraction of an environmental good (fuelwood). This indicated whether a decrease in access to fuelwood or deforestation would cause trade-offs with household food production by revealing the nature of the relationships among major livelihood activities (fuelwood collection, agriculture, and off-farm employment). Second, this permitted an empirical analysis of the effects of fuelwood scarcity on household energy expenditure patterns and fuel choice decisions. Third, it permitted household bio-based energy use and the nature of energy substitution to be examined and to better understand the effects of various socio-economic factors on household bio-based energy use and how fuelwood scarcity affects household bio-based energy use. The analysis results also facilitated consideration of how policies that improve access to electricity and promote improved efficiency biomass stoves could influence household bio-based energy use. Together these insights helped to evaluate the welfare effects of household bio-based energy utilization and the policy implications of potential interventions to address rural energy problems and to consider the synergies and how to reduce the risks associated with the water-energy-food nexus.

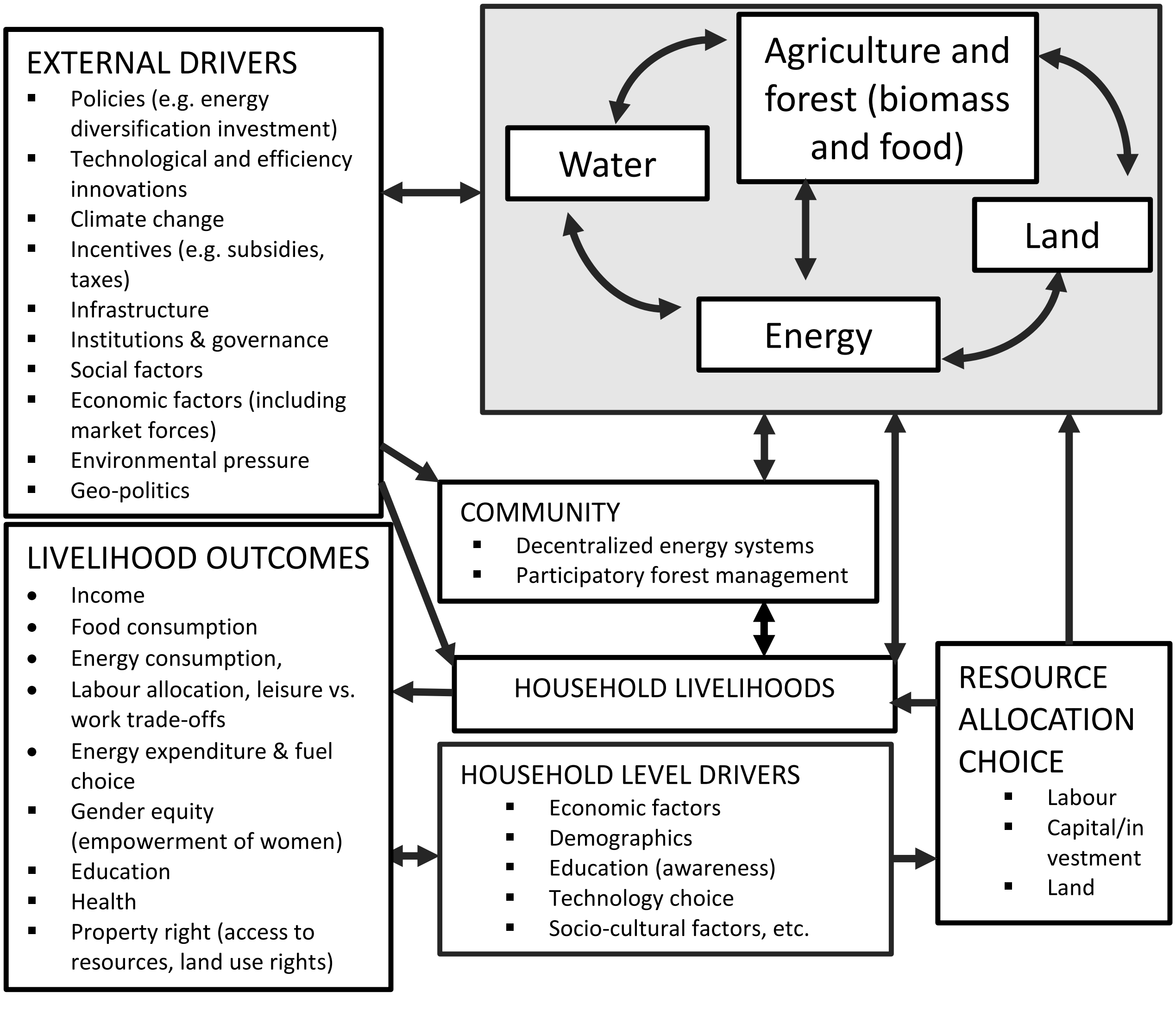

Figure 1.1. Conceptual framework: households within the water-energy-food nexus

Sources: Adapted from Hoff (2011); Brazilian et al. (2012); von Braun, (2013); Rasul (2014); Ringler et al., (2014)

Note: Welfare effects include the consumption of energy, food and water (quality and quantity), price effects, the substitution of goods, leisure vs. work trade-offs, and health

Households interact with the water-energy-food nexus in different ways. First, with limited land, labour, and capital resources, households are assumed to make decisions about the production and consumption of energy and food simultaneously. Such decisions could be practiced individually or within a collective community context (e.g. decentralized renewable energy generation and use). Households make resource allocation decisions based on comparisons of the expected returns, which in turn are expected to affect their welfare. Second, households consume energy, food, and other goods. Changes in the prices of those goods also affect household welfare. For instance, access to modern forms of energy and employment contribute to improvements in household welfare, but large-scale investments that contribute to deforestation or fuel scarcity negatively affect rural household livelihoods. Thus, households are expected to maximize utility by allocating more labour to activities and/or leisure, the use of energy to cook meals, and the consumption of other goods and services.

Competition for labour may arise due to fuelwood scarcity or environmental pressure. To cope with competitive pressure households may use agricultural waste for energy, which can cause trade-offs with food production because agricultural waste is often used for soil fertility management (Rasul, 2014). Biomass use can be considered at two scales: among households and nationally. At the household scale biomass is used to meet subsistence energy needs and as a complement to food production. Modern forms of biomass energy such as biogas, electricity, and charcoal briquettes can play a vital role in overall energy security. This study investigated strategies for enhancing the efficiency of biomass use at the household scale and modern biomass energy generation within the energy sector model framework.

Household energy use was evaluated explicitly using the AHM. The model was structured to explore the relationship between energy and food production by examining labour allocation. The model was also used to examine household biomass energy use, substitution, fuel choice, and related issues. The analysis also enabled evaluation of the effects on household biomass energy use of policies that improve access to electricity and that promote the use of improved efficiency stoves.

1.5. Organization of the study

The dissertation includes five chapters. Figure 1.2 describes the dissertation structure and core issues addressed. The introduction, background, research problem, research objectives and questions, and conceptual framework of the dissertation are presented in Chapter One. The AHM and the demand and supply perspective analyses of biomass energy utilization and its effects on livelihoods at the household level are presented in Chapter Two. In Chapter Three the dynamic linear programing energy sector model for solid biomass and investment on the power sector in Ethiopia is presented. Chapter Two and Chapter Three are linked by the use of elasticity values for household biomass energy consumption with respect to improved efficiency biomass stoves and electricity. Chapter Four presents the assessment of institutional arrangements, strategies, and collective action that are appropriate for decentralized renewable energy generation, and energy use among remote rural communities of Ethiopia. Shadow prices from Chapter Two and Chapter Three are used to analyse the costs and benefits of decentralized and private biogas systems in Chapter Four. Chapter Five presents a brief conclusion of the dissertation by summarizing the main empirical findings, offering policy recommendations, and identifying future research needs.

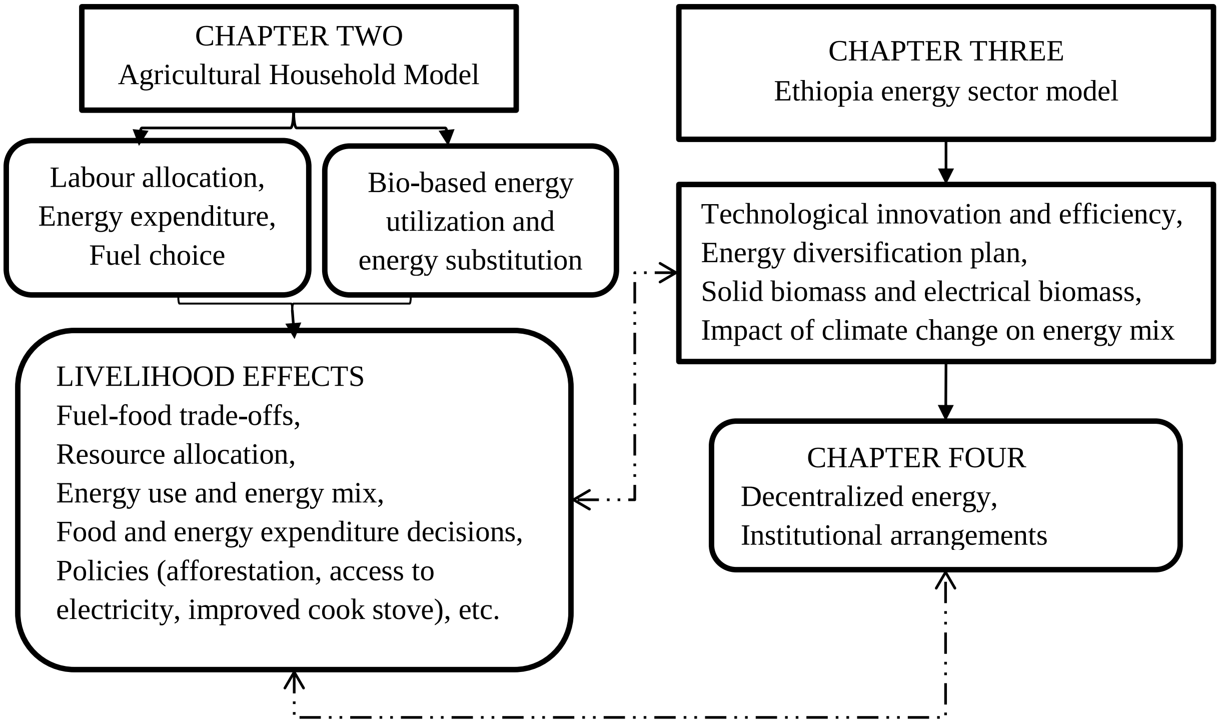

Figure 1.2. **Organizational structure of the dissertation**

Chapter Two

Household bio-based energy utilization and energy mix behaviour, and related linkages with food security and welfare effects

2.1. Introduction

Lack of access to clean energy is a major driver of widespread extreme poverty in Sub-Saharan Africa. Ethiopia is one of the few remaining countries in the world where the majority of the population continues to be reliant on traditional solid biomass energy use (IEA, 2013). Economically deprived rural households have few energy options. The vast majority of households use fuelwood as their main energy source in combination with agricultural fuels such as crop residues and cattle dung in areas where fuelwood is scarce. This component of the study examined the linkages among fuelwood scarcity, household energy substitution, and household livelihoods.

Reliance on solid bio-based energy resources is often linked to poverty, the lack of modern energy alternatives, and a web of other factors. Modern fuels are often used alongside traditional biomass fuels, but have failed to displace solid biomass energy in many developing countries, which supports the 'fuel stacking' concept (Heltberg, 2005; Mekonnen and Köhlin, 2008; Guta, 2012a). These studies found that access to modern energy options assocated with improved household welfare. However, there are not any published research findings on the linkages between biomass scarcity or changes in the shadow opportunity costs and household welfare, which can be reflected in changes in household resource allocation, energy expenditures, fuel choice, energy use, and energy substitution.

The effects of fuelwood scarcity on household welfare are poorly understood. With unprecedented rates of deforestation in Ethiopia, fuelwood scarcity is inevitable, particularly in highland areas where a majority of the nation's population resides. To date there has not been any empirical research on the consequences on fuelwood scarcity on household welfare due to foregone agricultural food production. Hence, empirical analysis is needed to better understand the linkages between agriculture and rural energy consumption from a household perspective. There is also limited literature information on the trade-offs between fuel and food production from the perspective of competitive labour allocation and energy demand or substitution in rural Ethiopia.

The effects of fuelwood scarcity or increases in the labour required for fuelwood collection on agricultural production or food security and the impacts of off-farm employment on household energy substitution and energy choice have not received much attention in the literature (Shi et al., 2009). The role of off-farm employment on energy substitution is also ambiguous. For instance, some studies have found that off-farm employment policies encourage rural household fuelwood substitution (Bluffstone, 1995; Wang et al., 2012). One study from poorer regions of rural China, however, found that increased off-farm employment opportunities did not necessarily promote rural energy transition (Shi et al., 2009). There has also been limited empirical research on the factors that drive fuelwood substitution in developing countries (Wang et al., 2012), or on the impacts of external determinants of household energy choices such as environmental conditions, consumer markets, and existing government policies (van der Kroon et al., 2013). There are a multitude of social, cultural, lifestyle, economic, and perception barriers to energy switching behaviour at the household level.

This study examined both supply and demand factors associated with household bio-based energy use and evaluated the influence of policies related to energy (electricity) access and improved efficiency biomass stoves on biomass energy use in rural Ethiopia. There is only limited understanding of the influence of such energy policies on rural household traditional biomass energy use in Ethiopia. Household welfare effects were investigated by examining shadow price elasticity to better understand the impacts of fuelwood scarcity or changes on household labour time allocation, energy expenditures, and fuel choice, as well as on household bio-based energy use and inter-fuel substitution.

In this chapter the following specific questions were addressed in the analyses. What are the determinants of traditional bio-based energy use at the household level? What are the linkages between household energy use and food or agricultural production? What types of substitutions occur among bio-based energy resources at the household level? There were two specific related objectives: (i) to examine the effects of fuelwood scarcity on household labour allocation among fuel collection, agricultural activities, and off-farm employment; and on per capita household energy expenditures and fuel choice, (ii) to analyse household bio-based energy use, the effects of various determinants of household energy use, and energy substitution behaviour.

2.2. Study site characteristics

A field survey was conducted on geographically heterogeneous households, ranging from coffee rich Gedeo in the Southern Nations, Nationalities, and Peoples' region (SNNP), Great East African Rift Valley (GEARV) villages in the Oromia region, and a more typical northern highland example of Basona Worena in the Amhara region. There is a diversity of biomass fuel use across these sites. Ethiopia has five agricultural zones: the cold highlands or 'Werch' zone above altitudes of 3,000 m (asl), the highland or 'Dega' zone within a range of 2,500–3,000 m, the middle highland or 'Weina Dega' zone within a range of 1,500–2,500 m, the semi-arid lowlands or 'Kolla' zone below 1,500 m, and finally the desert or 'Bereha' zone, which includes arid and other semi-arid lowlands. The geographic locations of the study sites are described in Table 2.1.

Basona Worena is a *woreda*[1] (district) situated in the eastern highlands of Ethiopia in the North Shewa Zone of Amhara, which are part of the continuum that includes the northern highlands. Four villages in Basona Worena were included in this study (Milkii, Kormergefia, Karafino, and Bokafia). Basona Worena borders the GEARV in the east. The northern highlands encompass the Siemen Mountains where the country's highest mountain, Ras Dashen, is located. Most of

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[1] *Woreda* is a district or administrative unit along the geopolitical scale following region and zone in the Ethiopian administration hierarchy that is composed of two or more *kebeles* or peasant associations.

Basona Worena is within the highland Dega agricultural zone, with a mean elevation of 2,714 m (asl), however, according to information provided by local administrators 2% of the area belongs to the highest agricultural zone (Werch). Two per cent of the area pertaining to these villages is mountainous and the remaining area is a plateau. The North Shewa Zone of Amhara has some of the coldest weather conditions in Ethiopia.

Table 2.1. Locations of the Ethiopian study sites

Study site	Latitude	Longitude	Geographic location relative to Addis Ababa
Basona Worena	N09°27'32"–10°04'50"	E39°15'28"–39°44'31"	130 km Northeast
Udee	N08°21'54"–08°56'02"	E38°45'07"–39°12'21"	55 km East
Trirufe	N07°05'20"–07°22'19"	E38°24'25"–38°49'37"	245 km South
Addado	N06°06'28"–06°22'38"	E38°17'34"–38°26'52"	386 km South

The villages of Udee and Trirufe are both located in the GEARV area of Oromia. Both sites are in the mid-altitude Weina Dega agricultural zone. Udee is located between 1,800 m and 1,900 m (asl) in the Eastern Shewa Zone of Oromia and is bisected by the main road connecting Addis Ababa to Djibouti. Udee is located about 10 km from the town of Debre Zeit. Trirufe was formerly attributed to the Eastern Shewa Zone of Oromia, but is now considered part of the Western Arsi Zone, which borders the SNNP to the south. Trirufe is situated at about 12.5 km north of the town of Sheshemene.

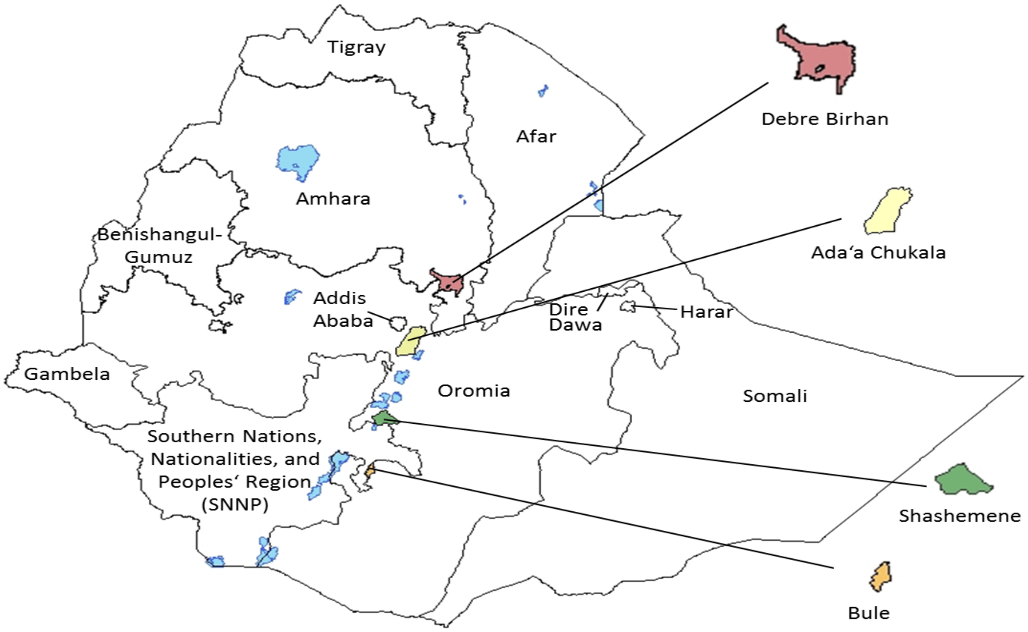

Figure 2.1. Geographical locations of the study sites in Ethiopia

The Gedeo Zone of SNNP is a renowned coffee producing area located along the eastern escarpment of the GEARV. Situated in the eastern tip of SNNP, Gedeo is surrounded by Oromia except to the west. Addado is the most densely populated ‘peasant association’ (village) in Gedeo. The Bule district occupies the eastern tip of Gedeo near the border with Oromia. Addado is situated about 20 km from the town of Dilla and 8 km from the town of Bule.

The total population of the East Shewa Zone of Oromia was 1,159,062 in 2007, of which about 11% (130,321) inhabited the town of Adda’aa Chukkalla (CSA, 2007). Adda’aa Chukkalla had an estimated population density of 217.3/km^2, which is greater than the local average of 181.7/km^2 (CSA, 2005). Some of the social variables and *woreda* characteristics are described in Table 2.2. A land-use survey in East Shewa conducted by the Oromia regional government found that about 51% of the area is arable, 6.4% is pasture, 7.4% is forest cover, and the remaining 34.8% is degraded or unsuitable for other land uses. Adda’aa Chukkalla is close to the capital, giving it relatively good access to infrastructure, markets, and facilities. This was reflected in better economic conditions relative to other *woredas* (Table 2.2). In 2007 the *woreda* of Sheshemene Zuria had a total population of 246,774 (CSA, 2007). In contrast to Adda’aa Chukkalla, where about 94% of the population is Christian; about 86.5% of the residents of Sheshemene Zuria are Muslim. Sheshemene is the most densely populated *woreda* in the zone at about 447.6/km^2, which is more than double the local average of 181.7/km^2 (CSA, 2005). Approximately 65% of the *woreda* is arable, 15% is pasture, 2.4% is forest cover, and the remaining 16.6% is degraded or unsuitable for other land uses.

Table 2.2 Demographic and geographic characteristics of the study site *woredas* (districts) in Ethiopia

Woreda	Population		Area (km^2)	Population density (#/km^2)
	Men	Women		
Adda’aa Chukkalla	67,869	62,452	1,750	217
Sheshemene Zuria	123,057	123,717	759.53	447.6
Bule	52,910	52,282		699.84 (Gedeo Zone)
Basona Worena	61,924	59,006	1,208.17	128

Sources: CSA (2005), CSA (2007)

In general the Gedeo Zone is very densely populated and the Bule *woreda* had a population of about 105,192 in 2007 (CSA, 2007). The largest religious group is Protestant Christian (75.23%), followed by Orthodox Christian (7.45%), Muslim (1.43%), Catholic Christian (1.29%), and the remainder (15.38%) were not religiously affiliated (CSA, 2007). In 2007 Basona Worena had a population of 120,930 among 27,753 households with a mean family size of 4.36 (CSA, 2007). This *woreda* had the lowest population density of the study sites at about 100/km^2. The entire population of Basona is Orthodox Christian and ethnically almost all rural residents are Amharan.

Agriculture is a common economic activity in all of the study sites. Mixed agricultural systems of crop production and animal husbandry are the main livelihood means. Teff, an indigenous staple crop, is commonly cultivated in Udee, which is a major teff supplier to the capital and the *woreda* of Bishoftu. In Basona Worena barley is the main crop. In Addado livelihoods are almost entirely dependent on the production of coffee, ensete, and to a limited extent on crops like maize, which is cultivated manually on a small-scale basis. Livestock husbandry is not a common economic activity in any of the study sites.

2.3. Agricultural Household Model, bio-based energy production and utilization, drivers and welfare effects

2.3.1. Conceptual framework

The conceptual framework of the research presented in this chapter is depicted in Figure 2.2. Household decisions are made regarding labour, land, and capital resource allocation to energy resource collection, agricultural production, and off-farm employment to earn income that can be used to purchase modern forms of energy, food, and other goods. The impacts of fuelwood scarcity on household livelihood arise from different angles. Increasing environmental pressure is expected to provoke labour reallocation among activities as labour demand for collecting fuelwood increases. This, in turn, is expected to affect household productivity and food security. Inter-temporal household decisions may include growing trees for fuelwood on marginal land; investing in an improved efficiency biomass stove or some other form of renewable energy. In the short term households may respond to increasing fuelwood scarcity by reducing the consumption of bio-based energy. Energy is a prerequisite for cooking food, therefore fuelwood scarcity affects household food consumption. This effect may result in a dietary shift as households opt for more easily cooked foods. This may result in poorer nutrition, particularly among children. Households may use improved biomass efficiency stoves to cope with fuelwood scarcity or else they may increase expenditures on biomass energy or modern energy alternatives in order to substitute or complement fuelwood they can collect. This in turn means that the implicit shadow costs of fuelwood collection, agricultural activities, and off-farm employment affect household inter-substitution and fuel choice. Fuelwood scarcity might also affect livelihoods through gender dimensions, education, and/or environmental pressures.

Food is produced from agricultural activities and/or purchased from markets. Food production requires household labour and energy inputs for cooking. Bio-based energy is typically used to cook food. Energy is also required for agricultural production. In a subsistence economy energy use for agricultural production is typically manual labour or draft animal power. Electricity is also used for pumping irrigation water and in many aspects of mechanized agriculture. In some of the study sites households used electricity for commercial purposes like milling, operating shops, and other off-farm private business efforts that contribute to household incomes. Peasant households also use agricultural fuels to complement fuelwood. The substitution of agricultural fuels for fuelwood is expected to cause trade-offs, as they are often used as soil supplements for agricultural production (soil fertility maintenance).

The empirical analysis is based on an AHM used to investigate the impacts of implicit shadow wages, prices, and exogenous factors on: (i) household resource allocation (principally labour allocation); (ii) household energy expenditures and fuel choice behaviour; and (iii) bio-based energy utilization and energy substitution. Household stove choice, the type of energy used (access to modern energy), and food and labour allocation trade-offs all affect livelihoods. Households may also sell agricultural output and/or biomass resources in addition to engaging in off-farm work. Exogenous factors can be grouped into household-specific factors such as education, demographic composition, and preferences, as well as community-specific factors such as local population density, institutions, markets, access to modern energy options, availability of biomass, and forest governance institutions and user rights. These factors are expected to affect household resource allocation, consumption decisions, and fuel choices.

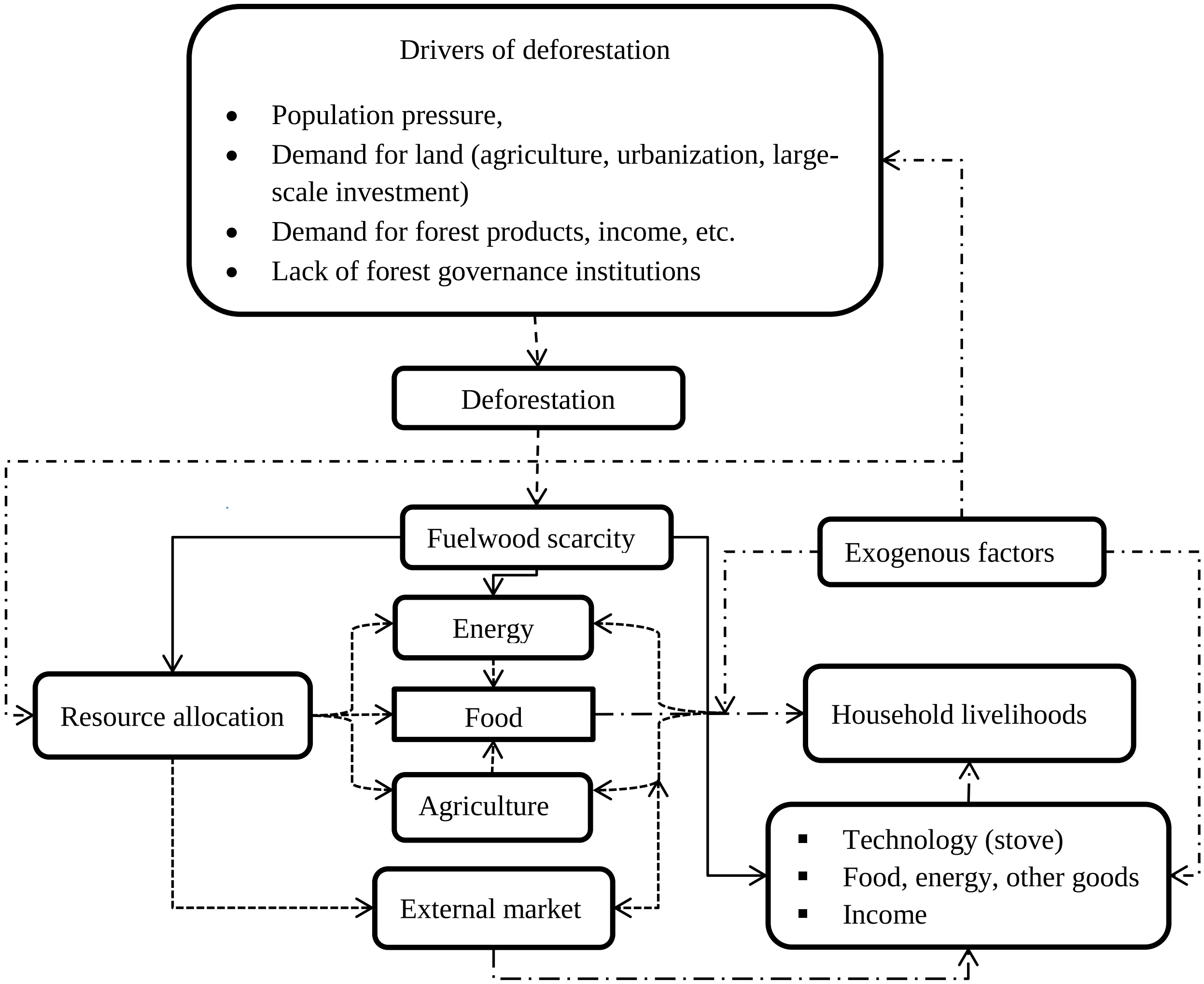

Figure 2.2. Conceptual framework of household bio-based energy use and livelihood effects

Note: Dashed lines show the effects of deforestation on fuelwood availability, mixed dash and dotted lines show the effects of socio-economic exogenous variables; square dotted lines show the linkages (resource allocation, biomass energy allocation) among energy, food/agriculture, and external markets; solid lines show the effects of fuelwood scarcity, and finally the long mixed dash and dotted lines show livelihood effects

Households are expected to maximize the utility of food consumption that requires energy as an input, leisure activities, and the consumption of other goods. Household decisions about the choice of whether to work or engage in leisure activities depend on implicit shadow wage valuations. Labour allocation is expected to be distributed among activities depending on the relative wages for energy collection, agricultural activities, and off-farm employment. Optimal household labour division is achieved when the marginal utility from leisure is matched by the expected gain from labour use among the different activities or the shadow wage or marginal revenue product of labour in the respective activity. At optimal conditions households cannot increase utility without reallocating labour among activities or else reduce leisure time. The assumption of joint household decision making implies that the AHM is appropriate for the analyses.

2.3.2. Relationships between poverty, rural household energy use, and environmental degradation in developing countries

Poverty is both a major cause and result of environmental degradation in developing countries (Scherr, 2000). However, the directionality of the relationship between the two depends on the type of environmental services considered. For instance, one recent study found that poorer households often depend heavily on environmental resources for subsistence use of products like fuelwood and food, and on products harvested from non-forest natural areas (Angelsen et al., 2014). In contrast the households in the highest income quantile and derived an income share from environmental resources that was approximately five times greater than households in the two lowest quintiles.

Various empirical studies have analysed the effects of household living standards or economic status on fuelwood consumption in developing countries and have reached highly variable conclusions. Different theoretical approaches have been taken for these efforts. First, the ‘inverted-U effect’ or the ‘environmental Kuznet’s curve’ (EKC) concept was applied to better understand how household extraction of fuelwood is related to changes in wealth status (Foster and Rosenzweig, 2003; Baland et al., 2007). Baland et al. (2010) studied the relationship between poverty and fuelwood collection among Nepalese households within an EKC framework and found that the improvement of living standards did not reduce fuelwood collection, but rather that fuelwood use could be substantially reduced by access to primary education and increased off-farm employment opportunities. These findings were contrary to the ‘poverty-environment hypothesis’ (PEH), which associates greater household reliance on environmental services (fuelwood use) with increasing poverty. They found that poorer families collected less fuelwood from forests than wealthier families. Evidence supporting EKC was only exhibited at the top end of the wealth distribution with respect to greater off-farm business assets (Baland et al., 2010). Fuelwood scarcity increases the opportunity costs or shadow prices involved in collecting fuelwood due to increasing distance to fuelwood sources. Wealthier households may respond to fuelwood shortages by switching to alternative energy resources provided that they are available and are appropriate substitutes.

Another family of theoretical approaches is the ‘poverty-environmental degradation nexus’ (PEDN) (Bardhan et al., 2002; Arnold et al., 2003; Demurger and Founier, 2011), which proposes that poverty reduction is a prerequisite for averting environmental degradation. Demurger and Founier (2011) found strong support for the PEDN in China, where household economic wealth had significant negative effects on household fuelwood consumption. The authors offered two main policy implications based on evidence of the PEDN identified. First, that poverty alleviation is a precondition for improving environmental sustainability. Second, that limiting access to nature reserves or other common property resources might exacerbate poverty, since poorer households more often rely on them and therefore suffer more when access is denied. Similarly, Sapkota and Oden (2008) found that among Nepalese households the poor were highly dependent on fuelwood. Conversely, time may have a greater economic value for members of wealthier households than for members of poorer households and therefore the shadow price of using fuelwood may also be higher (Baland et al., 2010), therefore, the overall effects of wealth or assets like land and cattle may be indeterminate.

2.3.3. Determinants of household bio-based energy use in developing countries

In many parts of developing countries fuelwood has been considered a ‘free’ good that is most commonly collected by households using family labour. Increases in human populations have resulted in dwindling forest cover due to the lack of appropriate forest resource management combined with greater demand for forest products and land for agricultural production. In overpopulated areas like the Ethiopian highlands fuelwood access is constrained by both internal household factors such as labour scarcity, and external environmental factors including forest scarcity and the limited availability of alternative fuels. In addition to opportunity costs there are intricate factors that explain household energy use and inter-fuel substitution. Household assets like land and livestock play important roles in energy use and substitution. The availability of agricultural fuels is partly determined by cattle abundance and crop types. Land and cattle abundance are often considered as proxies of household wealth; households with more cattle tend to earn greater income and therefore are expected to be more likely to purchase modern commercial substitute fuels. This also implies that the opportunity costs of collecting fuelwood may be higher for such households. In contrast, raising cattle and collecting fuelwood in many Ethiopian villages are activities that can be performed complementarily in communal forests or grazing areas. The complementary nature of the two activities makes the opportunity cost or shadow price lower. For instance, among Indian (Dayal, 2006) and Namibian households (Palmer and Macgrego, 2009) the two activities were complementary (there was a positive correlation between them), although it was not significant in the latter case.

In rural Ethiopia the reduction of extreme poverty has been found to discourage household dependence on traditional biomass fuel use when appropriate alternative commercial energy sources are available (Guta, 2012a). Fuel substitution of dry cattle dung or crop residues for fuelwood has been investigated among Namibian (Palmer and Macgrego, 2009) and Ethiopian households (Mekonnen, 1999; Mekonnen and Köhlin, 2008). These studies arrived on the conclusion that these lower quality fuels are not fuelwood substitutes. There is a lack of consensus about whether fuelwood energy is a normal or inferior good. Studies from China and Uganda describe fuelwood as an inferior good, and found that rural household wealth was negatively associated with fuelwood use (Demurger and Fournier, 2011; Lee, 2013). Other studies have found fuelwood to be a normal good (Mekonnen and Köhlin, 2008; Shi et al., 2009). The transition from traditional biomass fuels to more refined commercial alternatives is part of the process of economic growth (Macht et al., 2007; Lee, 2013), but fuel transition in rural Ethiopia is also constrained by the lack of access to alternatives (Guta, 2012a). Demurger and

Fournier (2011) indicated that the own-price effect of fuelwood consumption behaviour is important and that the importance of the price effect increases with household income.

One study in China found that livelihood changes, primarily greater off-farm employment and agricultural specialization, lead to fuelwood substitution (Wang et al., 2012). Similarly in rural Nepal greater off-farm employment opportunity was associated with fuelwood substitution (Bluffstone, 1995). In Uganda evidence of the energy ladder was observed (Lee, 2013). That study found that household use of solid and transitional fuels showed an inverse-U pattern as household income increased, while electricity consumption had a direct positive relationship with income. In contrast, despite substantially higher cost in comparison to modern fuels, fuelwood users continued to purchase fuelwood from markets in Guatemala (Heltberg, 2005). Therefore, the household decision to switch from traditional biomass use to modern alternatives may depend on the external biophysical environment, the external political and institutional-economic contexts, and internal household opportunities (van der Kroon et al., 2013).

2.3.4. Theoretical framework of the Agricultural Household Model

The neoclassical assumes that an agricultural household engages in production and consumption decisions simultaneously. Non-separable agricultural household models have been used extensively for studying household behaviour in developing countries (Singh et al., 1986; Jacoby, 1993; Sadoulet and de Janvry, 1995; Kein, 2010). Household behaviour is consistent with a non–separable model if household production decisions (i.e. labour choices, production, inputs and outputs) are affected by preferences and demographic composition (Kien, 2010).

Many studies have used non-separable models to investigate bio-based energy production and use in developing countries (Bluffstone, 1995, Cooke, 1998; Mekonnen, 1999; Heltberg et al., 2000; Hyde and Köhlin, 2000; Pattanyak et al., 2004; Chen et al., 2006; Palmer and Macgregor, 2009). Household economic decisions regarding production, consumption, and labour allocation are presumed to be made jointly (Hyde and Köhlin, 2000). That study recommended that in dealing with fuelwood scarcity, it is better to consider wages and collection time than prices. Models have been widely adapted to address problems related to market failures or imperfections, especially for environmental valuations. In this particular case there is a flow of goods and services from the environment to the household economy; variation in fuelwood use is typical of cases where market imperfections are prevalent.

Starting with Becker’s (1965) pioneering article on the theory of time allocation, a number of economists have analysed household time allocation decisions in the framework of household production as well as the utility maximization perspective. Becker explicitly introduced time as an input in a household final good production function and found that competing activities act as constraints that can make time a scarce economic resource. Markets for key services and products are limited in remote rural villages Ethiopia. The AHM was designed to examine household labour allocation decisions among competing livelihood activities, household biomass energy utilization, energy and food expenditures, and energy mix behaviour and the resulting welfare effects. The majority of rural households collect fuelwood using family labour, making collection cost implicit (i.e. an opportunity cost of labour time).

The model describes peasant household engagement in fuelwood collection, agricultural activities, and off-farm employment. The model was applied for an analysis of rural Chinese household energy use by Chen et al. (2006). Household utility is defined as a function of energy services like household consumption of cooked food, heating, and illumination represented by (C_Z(.)), the consumption of other goods (C_M), and household leisure time (C_l). Fuel production and use are largely influenced by household-specific time opportunity costs. For agricultural fuels, apart from the opportunity cost of collecting cattle dung (from communal grazing area) these are negligible as they are non-separable from agricultural production. Household preference is influenced by specific factors such as wealth and demographic factors (Z^H). The utility function is specified as:

$$U = U(C_Z(.), C_M, C_l; Z^H) \tag{3.1}$$

Households are expected to maximize utility subject to four main constraints in addition to non-negativity constraints. The first constraint stems from the production technologies for agricultural output and fuelwood. Fuelwood production technology is a concave function of labour time spent on fuelwood collection (L_F) and the availability or number of trees cultivated on private property or forest access indicators (Z^F).

$$q_F = q_F(L_F, Z^F) \tag{2.2}$$

Agricultural production technology is a primary input expressed as a function of labour time (L_A), and agricultural residues used as organic fertilizer and fodder are specified as (q^i), while other inputs like chemical fertilizer and oxen ownership are presented by (Z^A).

$$q_A = q_A\left(L_{A,} q^i;\ Z^A\right) \tag{2.3}$$

Total agricultural waste generated is given as a fixed proportion of agricultural output as ($\psi q_A(.)$). Agricultural biomass allocated to agricultural production is (q^i) and agricultural biomass used by households as energy is (q_{AF}). Biomass waste and residue use by households is expressed as:

$$q_{AF} + q^i \leq \psi q_A(.) \tag{2.4}$$

Energy is produced from three sources. Energy production technology for $\mathcal{F}$ depends on fuelwood consumed (q_F); agricultural fuel consumed (q_{AF}); and purchased energy sources like electricity, kerosene, fuelwood, and charcoal (C_E), conditioned by ownership of an improved efficiency biomass stove (S). The energy service enters the utility function through the utility it delivers, such as cooked food, heating, or illumination, and is expressed as:

$$C_z(.) = \mathcal{F}(q_F, q_{AF}, C_E; S) \tag{2.5}$$

Households face a cash income constraint specified as:

$$P_A q_A + \pi_B + wL_O + \pi_g = P_M C_M + P_E C_E \tag{2.6}$$

where, C_M represents purchased consumable commodities including food and energy; P_M, P_E and P_A are the prices of purchased commodities, the price of purchased energy, and the price of agricultural outputs respectively; w is the wage rate; π_g is non-labour or exogenous income and savings, and π_B represents income from biomass sales. Households sell biomass and earn income from timber, standing trees, fuelwood, or other products. It is difficult to distinguish the market prices of fuelwood and agricultural fuel from the data. Households can earn income from biomass by selling it in urban centres, and these wages were used to predict the shadow wage and price.

The final household time constraint is expressed as the sum of labour time allocated to fuelwood collection (L_F), agricultural activities, off-farm employment (L_O), and leisure (C_l). Total household labour time (L_h) was formulated as:

$$L_h = L_A + L_F + L_O + C_l \tag{2.7}$$

The specific assumptions are that: (i) energy sources are substitutable; (ii) using agricultural residues and waste as energy reduces agricultural production; (iii) the use of labour for any productive activity reduces leisure; (iv) $Q_A(L_A, 0; Z^A) > 0$ (i.e. if fuelwood is not available and a household still produces agricultural outputs while using all agricultural residues and waste for energy); and (v) the prices of tradable goods and wages are exogenous to households. In rural Ethiopia biomass collection is an activity that is often performed by women and children. Women and children are also important sources of agricultural labour, however, particularly during sowing and harvesting periods. Male and female labourers are assumed to be perfect substitutes in the model.

An optimal household solution is obtained by maximizing the household utility function subject to energy, leisure, food, and profit constraints; a non-negativity condition for energy use; the use of fuelwood, agricultural residues and waste for energy and as agricultural inputs ($q_j \geq 0 \; \forall \, j = F, AF, i, F;\; C_E \geq 0$); labour allocation choice ($L_j \geq 0, \forall \, j = A, F, O,$); the shadow values of constraints ($\lambda \geq 0$); and the consumption of goods that use energy as an input; and other goods ($C_M, C_z,\; C_l \geq 0$). Household consumption of food, energy, and leisure contribute to utility. By substituting $C_m = \frac{P_A q_A(L_A, q^i; Z^A) + \pi_B + wL_O + \pi_g - P_E C_E}{P_M}$ from the budget constraint in Eq. (2.6) and leisure by the labour constraint in Eq. (7) ($C_l = L_h - L_A - L_F - L_O$) into the utility function in Eq. (1), the Lagrangian was formulated as:

$$\max_{q_E, q_F, q_{AF}, C_m, L_A, L_O, L_F,\; l_h,} \mathcal{L} = U\left(\begin{matrix} \mathcal{F}(q_F(L_F;\; Z^F), q_{AF}, C_E), L_h - L_A - L_F - L_O, \\ \dfrac{P_A q_A(L_A, q^i;\; Z^A) + \pi_B + wL_O + \pi_g - P_E C_E}{P_M} \end{matrix} \right) - \lambda L_O \tag{2.8}$$

The equilibrium condition was derived from the first order conditions as:

$$\frac{\partial \mathcal{L}}{\partial L_F} = \frac{\partial U(\cdot)}{\partial \mathcal{F}(.)}\frac{\partial \mathcal{F}(.)}{\partial q_F}\frac{\partial q_F(.)}{\partial L_F} - \frac{\partial U(\cdot)}{\partial C_l} = 0 \tag{2.9}$$

$$\frac{\partial \mathcal{L}}{\partial L_A} = \frac{\partial U(\cdot)}{\partial C_M}\frac{P_A}{P_M}\frac{\partial q_A(.)}{\partial L_A} - \frac{\partial U(\cdot)}{\partial C_l} = 0 \tag{2.10}$$

$$\frac{\partial \mathcal{L}}{\partial L_O} = \frac{\partial U(\cdot)}{\partial C_M}\frac{w}{P_M} - \frac{\partial U(\cdot)}{\partial L_l} - \lambda = 0 \tag{2.11}$$

$$\frac{\partial \mathcal{L}}{\partial C_M} = -\frac{\partial U(\cdot)}{\partial \mathcal{F}(.)}\frac{\partial \mathcal{F}(.)}{\partial C_E}\frac{P_M}{P_E} + \frac{\partial U(\cdot)}{\partial C_M} = 0 \tag{2.12}$$

$$\frac{\partial \mathcal{L}}{\partial C_E} = \frac{\partial U(\cdot)}{\partial \mathcal{F}(.)}\frac{\partial \mathcal{F}(.)}{\partial C_E} - \frac{\partial U(\cdot)}{\partial q_M}\frac{P_E}{P_M} = 0 \tag{2.13}$$

Conditions 9–13 can be rearranged to obtain the equilibrium conditions described as:

$$\begin{aligned}\frac{\partial U(\cdot)}{\partial C_l} = \frac{\partial U(\cdot)}{\partial \mathcal{F}(.)}\frac{\partial \mathcal{F}(.)}{\partial q_F}\frac{\partial q_F(.)}{\partial L_F} &= \frac{\partial U(\cdot)}{\partial C_M}\frac{P_A}{P_M}\frac{\partial q_A(.)}{\partial L_A} \\ &= \frac{\partial U(\cdot)}{\partial C_M}\frac{w}{P_M} - \lambda\end{aligned} \tag{2.14}$$

$$\frac{\dfrac{\partial U(\cdot)}{\partial C_M}}{\dfrac{\partial U(\cdot)}{\partial \mathcal{F}(.)}\dfrac{\mathcal{F}(.)}{\partial C_E}} = \frac{P_M}{P_E} \tag{2.15}$$

Equation (2.14) describes the equilibrium condition of time use by agricultural households among agriculture, fuel collection, and leisure. The condition states that a household cannot increase leisure utility by shifting a unit of labour time between the two activities (agriculture and fuel collection) and leisure. It indicates that households allocate labour time to any activity until the marginal utility of labour for agriculture and fuelwood collection is equal to the marginal utility of foregone leisure. The comparison of this utility to off-farm wage depends on whether a household participates in off-farm employment. It is equal to the wage rate if a household participates; otherwise it is expected to be higher than the wage rate. The optimal condition provides the amount of fuelwood and agricultural fuel, the amount of labour used for the three activities (fuel collection, agriculture, and off-farm employment), and monetary income from agriculture, biomass sales, and off-farm wage employment. Households use biomass energy (fuelwood and agricultural fuels) for consumption and sale to generate income to purchase other forms of energy (charcoal, kerosene, electricity) and other goods. Household cash expenditures on consumption goods are represented by Eq. (2.15). That equation states that households cannot increase utility by shifting consumption from energy to other goods and vice versa. This is reflected in the equality of the ratio of the marginal utility of market goods to energy and respective prices.

2.3.5. Empirical econometric strategy

The reduced form of the equation is specified in Eq. (16), which defines household labour allocation and energy consumption as a function of prices, wages, household socio-economic variables, and other exogenous factors. In the non-separable model it is not possible to derive the functional form of the reduced form equations analytically (Singh et al., 1986; Chen et al., 2006). The empirical model is therefore assumed to be linear. The reduced form equation defines household energy consumption and labour time use for different activities jointly as a function of the market price of energy, non-energy goods, the price of agricultural outputs, and other exogenous factors explained above. In addition, in the non-separable AHM model the shadow wage of fuel collection, agriculture, and off–farm labour, and the price of bio-based energy are important explanatory variables. The reduced form equation was described as:

$$\left.\begin{matrix} C_E \\ q_F \\ q_{AF} \\ L_A \\ L_F \\ L_O \end{matrix}\right\} = \mathbf{\Gamma}\left(S, L_h, P_M, P_E, w_i', P_i', P_A, \pi_g, Z^A, Z^F; Z^H\right) \tag{2.16}$$

where w_i', and P_i' are vectors of the shadow wages and prices respectively. The likely effect of wealth, price, and other variables were discussed in the previous sub-sections (2.2.1, 2.2.2, 2.2.3) and also in Chapter One. Here the specific variables that were used in the empirical analysis are identified and their expected effects explained. Household use of an improved efficiency biomass stove was described by a binary variable (S) with a value of 1 indicating use and 0 if otherwise. Household use of an improved efficiency biomass stove was expected to reduce biomass energy consumption, but there is mixed evidence for this in the literature. The variable Z^H represents household characteristics and wealth. Household wealth includes livestock (poultry, cattle, shoats) in tropical livestock units (TLU), and land area owned in hectares. The variable π_g represents exogenous income or non-labour income that did not involve family labour. This consists of remittances, gifts, and assistance received by households. The effects of wealth on household labour time use, fuel choice, and bio-based energy consumption are expected to be indeterminate (can be positive or negative).

Household demographic characteristics included in the model were family size, the age of the household head, the education level of the household head above elementary school, the highest level of education of a family member, the share of each family with formal education, the ratio of dependents to adults, the highest education level achieved by a family member, and whether or not a family member achieved a high school or higher level of education. The effect of household family size on household labour allocation for fuelwood collection and bio-based energy use was expected to be indeterminate. This is because large family size may imply more labour available for fuelwood collection, however, cooking food for a larger family may result in economies of scale or lower per capita energy use. Education variables are expected to increase household use of modern energy and reduce the use of traditional biomass energy. It is assumed that education increases household awareness about the adverse environmental, health, and economic impacts of traditional biomass energy use. It is also expected to motivate households to adopt improved efficiency biomass stoves and the use of electricity and other modern forms of energy. The variable Z^A expresses factors that influence agricultural production other than labour, including fertilizer, livestock, and land area.

The variable Z^F represents the vector of variables that affect household fuelwood use other than labour. It primarily represents household access to forest reflected in the number of trees on private land and population density in the area, which is expected to affect biomass availability or the level of competition for forest resources. A greater number of trees on private land is expected to reduce labour time required to collect fuelwood, but the effect on the amount of bio-based energy consumption may be indeterminate. This is because a greater number of trees on private land may represent greater household income from fuelwood sales and increases in disposable income. Conditional on the availability of modern energy alternatives, increases in disposable income are expected to increase consumption of modern energy alternatives relative to biomass energy. Thus, the overall effect is expected to be indeterminate. High population density is expected to increase pressure on communal forest and grazing areas and reduce household access and use of bio-based energy.

The variable P_E represents the price of purchased fuels. The price of charcoal was incorporated in the household energy consumption function because approximately 14.5% of the households purchased it, but it was not sold by any of the sample households. The market price of kerosene was incorporated in household energy consumption because most of the households purchased kerosene. Electricity prices did not vary across villages. Household expenditures were considered in the empirical analysis to examine for a substitution effect for electricity. In Ethiopia the electricity price per unit is fixed, particularly for very low-income households, but for higher levels of electricity consumption the per unit price increases. Sample households were in semi-urban areas and consumed low levels of electricity; therefore prices did not vary significantly. The parameter estimate was taken as an approximation for elasticity.

The variable w_i' represents the vector of shadow wages for fuelwood collection, agricultural activities, and off-farm employment. Higher shadow wage implies greater household access to forest or fuelwood. The shadow wages were predicted for each of these categories from the observed income and labour supply of the corresponding activities as explained below. Shadow prices of fuelwood and agricultural fuels were used for the energy consumption analysis. The variable P_i' is a vector of the shadow price of fuelwood and agricultural fuel. The shadow price calculation is described in the following section along with the methods used to address the problem of endogeneity of the implicitness of shadow wages and prices.

To investigate the trade-offs between food security and household bio-based energy use the study examined livelihood implications in two ways; based on labour time allocated and labour share ($l_{iht} = \frac{L_{it}}{L_{ht}}$), with ($i = F, A, O$) as specified in Eq. (2.22) and the energy expenditure equation (Eq. 2.23), and household energy use and substitution as specified in Eq. (2.24). The shadow wages were predicted from household characteristics and used in the labour share equation following Fisher et al. (2005). The predicted shadow prices were also used in the energy consumption function. The dependent variable used for predicting shadow wage was computed by dividing income earned by households from the activity by the annual labour time used for that activity. Hence, for household (h) the observed wage return from activity (i) was given as:

$$w_{iht} = \frac{\pi_{iht}}{L_{iht}} \tag{2.17}$$

where w_{iht} represents the observed earnings per hour from the activity, π_{iht} is income from that activity, and L represents labour time allocated to that activity. For fuelwood the total household biomass income (π_B) was a suitable proxy. Shadow wage was determined by the interplay of factors such as demography, household preference for leisure, and the consumption of food and energy. The observed wages from Eq. (2.17) are used as a dependent variable in the first stage of the labour allocation model and energy and food expenditure equations, and to predict shadow price used in the analyses of household bio-based energy utilization. The shadow price predicted using Eq. (2.18) was used in the energy consumption function Eq. (2.33).

Two methods have been implemented to predict the shadow price of biomass energy. Cooke (1998) measured the scarcity of environmental goods by multiplying the wage rate by the amount of time spent per unit of environmental good collected. Mekonnen (1999) multiplied the marginal product of labour used for woody biomass energy collection by the shadow wage. The same approach was used by Teklewold (2012) to predict the shadow price of livestock manure use for soil fertility management. Damte et al. (2012) and Heltberg (2000) used time spent per unit of energy collected as a proxy for fuelwood scarcity.

This study provided an alternative by building on the predicted shadow wage to predict shadow prices. Instead of using the market wage rate, the marginal product of labour, and time per unit of energy collected, the predicted shadow wages for fuelwood and agricultural residues were multiplied by the time per unit of fuelwood and cattle dung collection to predict shadow fuelwood and agricultural fuel prices respectively. This approach offers a closer approximation because it is based on monetary value due to the fact that it is based on the predicted wage and thus takes into account selectivity problems and household characteristics. This also offers a consistent analysis of the fuel-food trade-off because it captures not only energy use, but also broader agricultural and off-farm activities from labour supply and energy consumption aspects. Moreover, it provides a more accurate measure of the elasticity of energy consumption and energy substitution, which helped to address the problem of endogeneity of wages and prices. Shadow price was predicted by using the formula:

$$\ell n P_{ih} = \ell n\left(w'_{ih} * \frac{L_{ih}}{q_{ih}}\right) \tag{2.18}$$

where w'_{ih} represents the predicted shadow wage, P_{ih} is the predicted shadow price of energy type i, q_{ih} is the amount of energy i used by the household, and L_{ih} is labour time spent on energy i production.

The empirical model was derived from the reduced form of Eq. (16). The empirical model was specified in various stages using panel and cross-sectional econometrics. There are three econometric methodological complications that needed to be addressed. First, is the problem of selectivity in the panel data for households that switch livelihood activity choices and changes in household composition over time. Before determining the methods for predicting shadow wage from the observed wage return, the presence of selectivity was tested by predicting the inverse Mills ratio from the participation (binary) equation with a probit model in the first stage of participation choice for each activity for each panel period and conducting a t-test of the significance of the parameter on the inverse Mills ratio in the wage equation. Accordingly, evidence of the existence of a selectivity bias was observed in the case of fuelwood and off–-arm employment; however, there was no evidence of a selectivity bias for agricultural activities.

The second econometric issue relates to endogeneity of the shadow wages. This indicates that identifying an instrument is a key aspect of the model. The relationship between the binary participation equation and wage equation was used to account for any gaps between the observed hourly wage and implicit shadow wage for any of the activities, and it provides a correction for the estimation of the shadow wage (Shively and Fisher, 2004; Teklewold, 2012). Economic theory directs the choice of instruments. The instruments should have an effect on wage, but should influence household labour supply only through wage. The analysis used three instruments and their interactions for controlling the endogeneity of shadow wages. These variables were the distance from villages to the nearest paved road, mean per capita income in the village (Jia and Martin, 2013), and a dummy variable of whether or not a village had an agricultural cooperative(s), and interactions among the variables. Household and community access to cooperative services and distance to the nearest paved road affect the shadow wage of labour allocation to activities (labour supply). It was expected that the higher mean per capita income in the village, the higher agricultural and off-farm wages would be. In contrast, increases in the distance between a village and the nearest paved road were expected to reduce wages. Accordingly it was expected to influence labour allocation to the livelihood activities. To estimate wage and labour supply, and energy and food expenditures, a robust Fixed Effect two-stage Least Square (FE-2SLS) model was applied. The model performed all tests for the validity of instruments.

The third econometric issue is to capture the simultaneity of labour allocation decisions regarding the activities. Activities are assumed to compete for household labour, which suggests that a systems approach should be implemented. Therefore, the main methodological complexity arises when households switch their livelihood activity selection over time. Though the FE-2SLS method can help to capture endogeneity and selectivity, it might not be appropriate in this specific case. This is because the FE-2SLS could not allow consideration of the simultaneity and competition between activities. In order to consider simultaneity and the competitive nature of the livelihood activities the joint labour time (cumulative hours per year) was estimated by using a Seemingly Unrelated Regression (SUR); and an Almost Ideal Demand System (AIDS) as proposed in Fisher et al. (2005) was used to estimate labour share based on predicted shadow wage. In this case to circumvent the problem of endogeneity and selectivity biases related to changes in household livelihood activities over time, two competing approaches from the literature were proposed for panel data. Following Wooldridge (1995), the first approach is based on the parameterization of conditional expectations by estimating level equations by implementing Heckmann type corrections for each year in the panel and controlling FE by incorporating the average time of the exogenous variables in the equations (Mundlak, 1978; Jia and Patrick, 2013). The second approach is based on matching selected households in first difference as proposed by Rochina-Barrachina, (1999). The shadow wages of off-farm employment and fuelwood collection were predicted following Wooldridge (1995), because selection problems were detected, the approach does not require differing, and it is based on level estimation (Dustmann and Rochina-Barrachina, 2007).

Household wage and labour supply were estimated in two steps. In the case of the FE-2SLS the wage equation in the first step is specified as:

$$ln(w_{iht1}) = \alpha_{0i} + \beta_{1ih}X_{ht} + \gamma_{ih}Z_{ht} + \ell_t\lambda_i(H_{iht2}) + \epsilon_{iht1}$$
$$i = 1,2,3;\ h = 1,2 \ldots N; t = 1,2 \quad \epsilon_{iht1} \sim Normal(0,1) \tag{2.19}$$

where i represents the activity (fuelwood collection, agriculture, off–farm work), h represents each household, t is the time period, X_{iht} is a vector of exogenous factors that influence participation, wage and labour supply excluding the instruments, Z_{ht} represents instruments that were included in the wages, but excluded from labour supply, $\lambda_i(.)$ represents the inverse Mills ratio based on H_{iht2} for each activity, and ϵ_{iht} represents idiosyncratic error variables such that $E(\epsilon_{iht1}/Z_h, \alpha) = 0, t = 1,2$.

The first stage probit equation is specified as:

$$d_{iht} = 1[\varphi_{1ih}X_{ht} + \theta_{ih} + \mu_{iht2} > 0] \qquad \mu_{iht2}/X_h \sim Normal(0,1) \tag{2.20}$$

Hence, the probit model is specified as:

$$d_{iht} = \rho_{i2} + \varphi_{1ih}X_{ht} + \omega_{ih} + \mu_{iht2}; \qquad d_{it} = 1\ (d^*_{iht} > 0);$$
$$\mu_{iht2}/X_h \sim Normal(0,1) \tag{2.21}$$

where $\beta_{1ih}, \beta_{2ih}, \gamma_{ih}\ \delta_{ih}, \ell_t, \rho_{i2}, \varphi_{1ih}, \varphi_{2ih},$ and θ_{ih} are unknown parameter vectors, and μ_{iht2} is an idiosyncratic error term. In this case the labour supply is specified as:

$$ln(L_{iht}) = \alpha_{0i} + \gamma_{ih}\ell n(W_{iht}) + \sum_{i \neq j} \gamma_{ijh}\ell n(W_{jht}) + \psi_{ih}X_{ht} + \ell_t\lambda(H_{iht}) + \epsilon_{iht} \tag{2.22}$$

where $\alpha_{0i}, \gamma_{ih}, \gamma_{ijh}, \psi_{ih}$ and ℓ_t are unknown parameters and ϵ_{iht} is an idiosyncratic error term. A simultaneous labour supply system estimation approach was also applied.

The labour system equation was used to investigate simultaneity or allow for correlation among activities. Fisher et al. (2005) argued that a systems approach is theoretically more justifiable as forest activities (in this case fuelwood collection) is one of several activities often performed simultaneously by household members.

A control function approach was implemented in which the shadow wage is predicted (w'_{jh}) from Eq. (2.6) for the system of labour supply equation by excluding the vector of instruments (Z_{ht}) and their time differenced outcomes ($\overline{Z_h}$). To control for panel heterogeneity the time differenced mean of all exogenous variables was incorporated into the SUR model and the AIDS model for labour share system equation. The Mundlak (1978) approach was used to calculate H_{iht2} and to conserve degrees of freedom. This was performed by replacing the term θ_{ih} with $\overline{X_h} + \omega_{ih}$. Hence, the probit and wage equation are specified as:

$$d_{iht} = \rho_{i2} + \varphi_{1ih}X_{ht} + \varphi_{2ih}\overline{X_h} + \omega_{ih} + \mu_{iht2}\,; \qquad d_{it} = 1 \;\; (d^{*}_{iht} > 0); \\ \mu_{iht2}/X_h \sim Normal(0,1) \qquad (2.23)$$

And the shadow wages were predicted from wage equation specified as:

$$ln(w_{iht1}) = \alpha_{0i} + \beta_{1ih}X_{ht} + \beta_{2ih}\overline{X_h} + \gamma_{ih}Z_{ht} + \delta_{ih}\bar{Z}_h + \ell_t\lambda(H_{iht2}) + \epsilon_{iht1} \\ i = 1,2,3;\; h = 1,2 \ldots N; t = 1,2 \quad \epsilon_{iht1} \sim Normal(0,1) \qquad (2.24)$$

where: $\overline{X_h}$ and $\bar{Z}_h$ are variables representing the mean of exogenous variables and instrumental variables respectively; β_{1ih}, β_{2ih}, γ_{ih} δ_{ih}, ℓ_t, ρ_{i2}, φ_{1ih}, φ_{2ih}, and σ_{ih} are unknown parameter vectors, and μ_{iht2} and ϵ_{iht1} are idiosyncratic error term.

The labour allocation equations for the three activities in the SUR model were specified as:

$$ln(L_{iht}) = \alpha_{0i} + \gamma_{ih}\ell n(w'_{iht}) + \sum_{i \neq j} \gamma_{ijh}\ell n(w'_{jht}) + \psi_{ih}X_{ht} + \xi_{ih}\overline{X_h} + \varepsilon_{iht} \qquad (2.25)$$

where *i* and *j* represent livelihood activities (fuel collection, agriculture, off-farm employment); α_{0i}, γ_{ij}, ψ_{ih}, and ξ_{ih} are unknown parameter vectors; activity i w'_{jht} denotes the predicted wage from livelihood activity *j*; and ε_{iht} is the error term that is expected to be correlated across equations such that $\varepsilon_{iht} \backsim N(0, \delta^2_{ij})$.

Joint household labour shares among the three activities estimated based on an AIDS model. In this case the dependent variable is the household share of labour time allocated to activity i (fuel collection, agriculture, or off-farm employment) given as: $l_{iht} = \frac{L_{iht}}{L_{ht}}$. The predicted wage rate (w'_{jh}) from Eq. (24) was used in the system of share equations by excluding the vector of instruments (Z_{ht}) and their time difference ($\overline{Z_h}$). The system of labour share equations can be analysed using an AIDS model in a similar fashion to commodity demand following Deaton and Muellbauer (1980). The pooled AIDS model for household systems of labour share equations was specified as a function of various determining factors as:

$$l_{iht} = \alpha_{0i} + \sum_{i \neq j} \gamma_{ij}\ell n(w'_{jht}) + \psi_{ih}X_{ht} + \xi_{ih}\overline{X_h} + \eta_{iht} \qquad (2.26)$$

where i and j represent livelihood activities; α_{0i}, γ_{ij}, ψ_{ih} and ξ_{ih} are unknown parameter vectors; w'_{jht} denotes the predicted wage from livelihood activity j; and ε_{iht} is the error term that is expected to be correlated across equations such that $\eta_{iht} \backsim N(0, \delta^2_{ij})$.

In the system of share equations, three sets of restrictions are required to be met by construction. First, the adding up condition is represented by the condition $\sum_j \alpha_i = \alpha_F + \alpha_A + \alpha_O = 1$, which ensures that the predicted labour share equations of all activities sum to unity. Second, homogeneity means that the labour share equations are invariant to proportional changes in all wages; described by $\sum_i \gamma_{ij} = 0, \sum_i \beta_{ih} = 0$, and $\delta_h = 0$. Third, symmetry restrictions mean that cross-wage effects are equivalent, $\gamma_{ij} = \gamma_{ji} \ \forall \ i, j$.

In earlier studies, one of the equations was dropped from the model during estimation to avoid singularity of the disturbance covariance matrix (Sadoulet and de Janvry, 1995). Poi (2012) developed a programme that addressed this problem in order to estimate all of the share equations jointly in a more consistent way, which was followed in this study. Pooling time series and cross-sectional data, AIDS produces theoretically consistent parameter estimates as it allows for possible cross-equation restriction because the equations are estimated simultaneously.

The empirical model in the energy expenditure analysis uses both continuous and discrete dependent variables to measure the welfare effects of fuelwood scarcity. The continuous variables are per capita energy and food expenditures in monetary metric. The discrete variable is energy choice. Shadow wages play an important role in household decision making. Higher shadow wage implies better household access to forest or fuelwood. The dependent variables used in the first stage were observed wages of the three activities (fuelwood, agriculture, and off-farm employment). The FE-2SLS model was used by incorporating the inverse Mills ratios for food and energy sources (e) for each year that were predicted using a probit model. The binary outcomes for per capita energy and food purchase decisions (d_{eht}) are specified as:

$$\begin{aligned} d_{eht} = \ & \rho_{e2} + \varphi_{1eh}X_{ht} + \varphi_{2eh}Z_{ht} + \omega_{eh} + \mu_{eht2}; \qquad d_{eht} = 1 \ (d^*_{eht} > 0); \\ & \mu_{eht2}/X_h \sim Normal(0,1) \end{aligned} \qquad (2.27)$$

Where d^*_{eht} represents latent dependent variables for energy and food purchase choices; ρ_{e2}, φ_{1eh}, and φ_{2eh} are unknown parameters; and ω_{ah} and ω_{eh} represent variables that capture unobserved household heterogeneity in activities and purchase choices respectively.

Then the per capita energy and food expenditure function is specified as:

$$C_{eht} = \gamma_{0e} + \sum_{i \neq e} \gamma_{ie} \ell n(w_{iht}) + \psi_{eh}X_{ht} + \ell_{et}\lambda_e(H_{eht}) + \varepsilon_{eht} \qquad (2.28)$$

where C_{eht} represents per capita expenditures on energy sources or food by household (h) in time period (t), $\lambda_e(.)$ represents the inverse Mills ratio calculated based on H_{eht} for household energy (biomass and kerosene) and food purchase choices; γ_{0e}, γ_{ie}, ψ_{eh}, and ℓ_{et}, are the unknown parameters of interest in the final stage of the FE-2SLS on which the analysis focuses, and ε_{eht} is an error term.

The discrete choice model of household energy choice was formulated to investigate the effects of fuelwood scarcity and other determinants of energy transition. Households maximize utility by choosing to purchase energy source f, among alternatives (F), and there is a latent conditional indirect utility (V'_{fht}) specified as:

$$\mathrm{V}'_{fht} = \sum_{i \neq f} \gamma_{if} \ell n(\mathrm{w}'_{iht}) + X_{ht}\theta_f + \kappa_f + \eta_{fht} \qquad f = 0,1,2,\dots F \tag{2.29}$$

where η_f is the unobservable idiosyncratic error term, κ_f is unobserved household heterogeneity, θ_f and γ_{if} are unknown parameters, and w'_{iht} represents the predicted shadow wage from Eq. (6).

This supposes that P_{fh} $(f = 0, \dots, 4)$ denotes the fuel category (i.e. 0 = purchase biomass or biomass mixed with modern energy options, 1 = electricity only, 2 = kerosene only, 3 = battery powered devices and others, 5 = a mix of any modern energy options (electricity, kerosene, battery powered devices and others). It was assumed that η_{fht} is identically and independently distributed (iid) across energy choice sets. Then the odd ratio is given as:

$$P_{fh} = \frac{exp^{(\sum_{i \neq f} \gamma_{if} \ell n(w'_{ih}) + X_h\theta_f)}}{\sum_{f=0}^{4} e^{(\sum_{i \neq f} \gamma_{if} \ell n(w'_{ih}) + X_h\theta_f)}} \tag{2.30}$$

Following the econometric rule and the assumptions specified above, setting the values of γ_{if} and θ_f to zero, the odd ratio for each choice ($f \neq$ energy category 0) is written as:

$$P_{fh/f \neq 0} = \frac{e^{(\sum_{a \neq f} \gamma_{fa} \ell n(w'_{ah}) + X_h\theta_f)}}{1 + \sum_{f=0}^{4} e^{(\sum_{a \neq f} \gamma_{fa} \ell n(w'_{ah}) + X_h\theta_f)}}, f = 1,2,3,4 \tag{3.31}$$

and for the reference group;

$$P_{fh/f=0} = \frac{e^{(\sum_{a \neq f} \gamma_{fa} \ell n(w'_{ah}) + X_h\theta_f)}}{\sum_{f=0}^{4} e^{(\sum_{a \neq f} \gamma_{fa} \ell n(w'_{ah}) + X_h\theta_f)}} \tag{2.32}$$

Finally, the cross-sectional econometrics are applied to estimate household energy consumption functions. For household (h), demand for biomass energy type (fuelwood, agricultural fuel and charcoal) (b) is specified as:

$$\ell nq_{bh} = \phi_{bh} + \sum_{b \neq j} \eta_{bj} ln(P'_{bh}) + \tau_b X_{bh} + \delta_b G_h + \omega_b X_C + \upsilon_{bh} ; \quad \upsilon_{bh} \sim Normal(0,1) \qquad (2.33)$$

where $\phi_{bh}, \eta_{bj}, \tau_b, \omega_b$, and δ_b are unknown parameter vectors; q_{bh} represents the amount of energy i consumed by household h; P_b and P_j are the shadow prices of energy options b and j respectively; G_h represents the interaction of assets (land and livestock) with the shadow wage; X_h represents other household-specific factors; X_C represents community specific factors such as population density; and υ_{bh} represents unobservable variables.

The econometric analysis is based on different econometric models specified above. First, the FE-2SLS in Eq. (2.22) is used to estimate annual labour time allocated to the three activities separately in section 2.5.2.1.1. The selectivity bias in household fuelwood or biomass sale, and off-farm employment participation choice, and (energy and food) purchase decision is corrected with the inverse Mills ratio predicted from probit model in Eq. (2.23) and Eq. (2.27). Second, the household joint labour allocation is estimated using the SUR in Eq. (2.25) described in section 2.5.2.1.2 and labour share equations is estimated using the AIDS model in Eq. (2.26) described in section 2.5.2.1.2. In these cases, the shadow wages were predicted for each activity based on Eq. (2.24) using the inverse Mills ratio from the probit model in Eq. (2.23). Third, per capita energy and food expenditures are estimated using the FE-2SLS in Eq. (2.28) described in section 2.5.2.2.1. Fourth, the multinomial logit model is used to estimate household discrete fuel choice in Eq. (2.30) described in section 2.5.2.2.2 using the predicted shadow wage from the FE first-stage wage equation that was corrected for selectivity using inverse mills ratio predicted from probit model in Eq. (2.23). Finally, the predicted shadow wages are used to predict shadow prices, which are used together with other exogenous factors in the energy consumption function as formulated in Eq. (2.33) described in section 2.5.4. The wage elasticity of each activity and the wage elasticity of substitution between activities were computed to evaluate the competition or complementarity among activities. Lastly, together with a detailed analysis of household energy consumption behaviour, energy mix decision, and energy and food expenditures, this helped to reveal household welfare implications.

2.4. Description of the data and sampling technique

Both primary and secondary data were used in the analyses. There were two types of secondary survey data: household-level base survey and national-level data. The base survey was from the 'Ethiopian Rural Household Survey' (ERHS) conducted in 2004. The ERHS is a well-known longitudinal survey in the country that was initiated in 1989 (Webb and von Braun, 1994). The survey period was characterized by the most severe warfare and famine in Ethiopian history. This survey included six villages in central and southern Ethiopia, with a total of 450 households. In the follow-up phase in 1994 the survey was extended to nine additional villages across the country for a total of 15 villages and 1,477 households. Five of the villages are in the Amhara region, two villages are in Tigray, four are in Oromia, and four are in the SNNP. The survey was repeated in all 15 villages in 1995, 1997, 1999, 2004, 2009, and 2011. The survey was stratified according to the main agricultural zones of Ethiopia, with one to three villages selected per zone (Dercon and Hoddinott, 2004). The survey efforts were supervised by the

Economics Department at Addis Ababa University, the Centre for the Study of African Economy (CSAE), the University of Oxford, and the International Food Policy Research Institute (IFPRI).

The surveys provided detailed data on household consumption and expenditures, assets, income, agricultural activities, land allocation, demographic characteristics, and other variables. Participating villages were selected based on various criteria, such as the diversity of farming systems, productivity, and vulnerability (Dercon and Hoddinott, 2004). The survey data have been used in many recent research efforts (Gray and Mueller, 2012; Guta, 2012a). After complete lists of the households in each village were obtained from village administrators, random samples of respondents were drawn based on the gender of household heads in proportion to the population of the selected villages. However, since the original survey was designed with multiple objectives, detailed information on the amount of fuel produced, consumed, or purchased was not available.

From September 2011 to January 2012 another survey of 221 households was conducted in three major regions of central and southern Ethiopia. At the time of this latest survey effort the most recent ERHS survey data available was from 2004. The selection of respondents, determination of sample size, and apportionment of the sample were based on a proportional sampling technique.

Despite efforts to link the two surveys, some relevant information was missing in the base year survey. In order to address the research objectives the study combined the 2011–2012 field survey and the ERHS 2004 data. For a detailed analysis of the amount of biomass energy produced and consumed only the field survey data were used. In addition to addressing important questions from the ERHS survey data, the field survey was designed to generate detailed information on household biomass energy production and consumption practices; as well as farming activities; labour and land allocation; economic and demographic characteristics; and expenditures on food, non-food goods, and energy. It was not possible to conduct a panel data analysis on household bio-based energy use because the ERHS 2004 lacked detailed data on biomass fuel use. The 2011 survey effort collected detailed household biomass energy use data.[2] Only the field survey data were analysed using appropriate econometric approaches in order to examine household biofuel consumption behaviour.

The next steps were to determine the study areas and samples. Multiple criteria were used to determine study sites, including: the diversity of biomass energy consumption, the desired number of respondents, and the patterns of energy utilization. One criterion was the sample sizes in the ERHS 2004 effort, because a sufficient sample size was needed to account for unavailable respondents (who may have moved or passed away during the interim). After carefully reviewing the ERHS database and other secondary sources, a pilot survey was conducted in July 2011 to identify potential study sites. Four villages were selected: two in Oromia, one in Amhara, and

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[2] The measurement of household biomass energy was obtained in local traditional units and later converted to kilograms. The conversion factors were established based on measurements taken in the closest urban centre for all biomass energy consumed in the study areas. Information obtained on household biomass energy use was collected a week before the survey was conducted. It was then aggregated into annual figures, although household biomass energy use may vary seasonally.

one in SNNP. The sampling method was based on the geography of southern and central Ethiopia, which is further segregated geopolitically into regions, zones, districts, and villages.

The next challenge was how to allocate the survey sample across villages, for which a pure proportional sampling method was used. The sampling objective was to survey about 210 households from the four villages. This sample size was proportionately distributed based on the ERHS sample size. Based on the list of names from the previous survey, the number of households chosen was based on $\left(\frac{N}{n}\right)^{th}$, where n was the current sample size and N was the base year sample size. A complete list of the study areas and sample sizes is given in Table 2.3.

Table 2.3. Ethiopian study areas and sample sizes (number of households)

Region	Zone	District or *woreda*	Peasant association	ERHS 2004	Sample size
Amhara	Northern Shewa	Basona Worena	Basona Worena[3]	169	81
Oromia	Eastern Shewa	Adda'aa Chukkalla	Udee	80	37
	Western Arsi	Sheshemene Zuria	Trirufe	90	43
SNNP	Gedeo	Bule	Addado	124	60

Source: ERHS (2004)

A complete list of households was used to select the survey respondents. Then the respective peasant association administrators were consulted to determine the availability of sample households. In cases of respondent unavailability, the next household on the list was chosen as a replacement. A total of 221 households were selected for the survey (Table 2.3): 36.2% were located in Oromia, 36.65% in Amhara, and the remaining 27.15% in SNNP. Due to missing key variables like income for some households, only 214 households were considered in this analysis.

2.4.Descriptive statistics

Addado had the lowest per capita income. A typical household in Addado earned about 1,506 Ethiopian Birr (ETB) (US$ 81.54) per year in 2011, which was about 48% of the income earned by counterpart households in Udee, where households had the highest per capita income of 3,124 ETB or US$ 169 (Figure 2.3). The mean annual earnings of Addado households were the lowest over both survey periods. Mean household earnings in Addado, Trirufe, and Udee grew at annual rates of 2.8%, 4.7%, and 4.8% respectively over the 2004–2011 period. In contrast, mean annual household earnings in Basona Worena declined at a rate of 1.3%. In addition to favourable agricultural conditions, this geographical advantage gives Udee greater access to modern infrastructure, inputs, investment activities, technological advantages, and markets, allowing farmers to earn higher prices for their harvests. Off-farm earnings were also high in Udee, likely due to greater access to investment or employment opportunities.

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[3] Basona Worena originally included four small villages (Milki, Koremergafia, Bokafia, and Karafino), however, the latter two villages became part of the town of Debra Berhan in 2011. Respondents were selected from all four villages based on the ERHS 2004 survey.

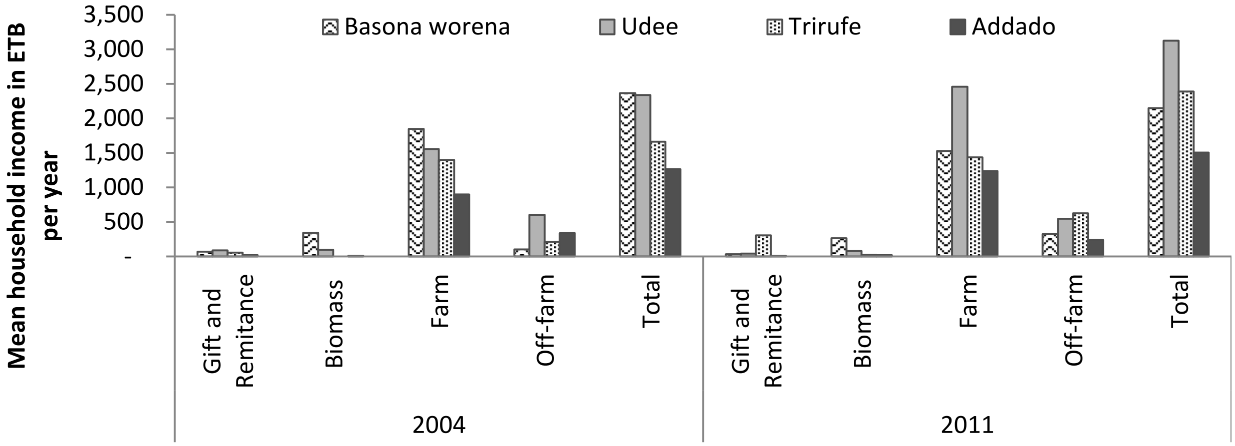

Figure 2.3. Sources of annual sample household earnings over time, in Ethiopian Birr

Agriculture was the major livelihood means, with household earning shares above 64% in Basona Worena in 2011 and 65% in Udee in 2004. However, the importance of agriculture dropped significantly for Trirufe and Basona Worena from 91% and 77% respectively in 2004 to 64% in 2011 for both. In contrast, agricultural earning shares rose from 65% to 80% in Udee over the same period. Basona Worena had the highest livelihood share from fuel sales. Cattle dung was the most commonly traded fuel in the *woreda* of Debre Berhan, representing about 16% of household earnings for both periods. Households in Udee derived about 4% from fuel sales in 2004 and 5% in 2011 (Table 2.4).

Table 2.4. Sources of annual sample household earnings by village and year (shares)

	2004				2011			
Activity	Basona Worena	Udee	Trirufe	Addado	Basona Worena	Udee	Trirufe	Addado
Agriculture[a]	0.77	0.65	0.91	0.72	0.64	0.80	0.64	0.80
Biomass[b]	0.16	0.04	0.00	0.01	0.16	0.05	0.01	0.01
Off-farm[c]	0.04	0.28	0.07	0.25	0.18	0.11	0.21	0.17
Non-labour[d]	0.04	0.03	0.03	0.02	0.02	0.04	0.13	0.02

Note: [a]Agriculture includes income from the sale of crops, livestock, and livestock products excluding dried cattle dung and crop residues

[b]Biomass refers to earnings from the sale of forest products (standing trees, timber, firewood, charcoal, etc.), dried cattle dung, and crop residues

[c]Off-farm is income from off-farm businesses and employment

[d] Non-labour includes income from the sale or rental of assets like land, interest on loans, remittances, gifts, and government assistance

Labour balance was calculated at the household level for illustrative purposes. Household agricultural labour demand was not constant throughout the year. From the labour supply perspective, the economically active labour supply also differs seasonally. Labour supply constraints depend on the number of family members capable of engaging in agricultural activities. In the case of children only non-school periods were considered because children spend nearly the whole day at school when it is in session. Another factor that influences farm household labour supply is family size. The mean family size for all study sites was 6.0 members in 2004 and 5.3 in 2011 (Table 2.6). At the regional level the mean family size in Oromia was 4.7 (CSA, 2005). According to the survey results, an average of three out of five household members were economically active, and an average of one member was engaged in domestic activities. It was assumed that children under the age of 18 spend their time in school except for a ten-week break from July 04 to September 11 and a mid-semester break from December 19 to January 01 (Gurmesa, 2011). Hence, the annual child labour supply was a period of approximately 12 weeks, for 8 hours a day, and 6 working days a week (6*2*2*8 = 192 hours per year). For the remaining two economically active family members, the total labour hours were computed as 6*2*2*8*12 = 2,304 hours per year. Other studies have followed a similar approach (Gurmesa, 2011).

The mean labour times allocated for the three activities increased over time (Table 2.6). The labour shares by activity are given in Table 2.5. Fuel collection labour shares increased in all villages; by about 22% in Trirufe and 17% in Udee. In Addado the share of fuelwood collection declined slightly (by 1%), but in Basona Worena it increased by about 5%. Cooperative forest management efforts were being implemented in Udee and in Trirufe, where four forest cooperatives restricted forest access. All sample households reported utilizing dried cattle dung as fuel in Basona Worena and crop residues as fuel in Addado. Agricultural and off-farm employment labour shares increased slightly over the same period.

Table 2.5. Labour activity shares by village and year among Ethiopian sample households

	2011				2004			
Activity	Basona Worena	Udee	Trirufe	Addado	Basona Worena	Udee	Trirufe	Addado
Fuelwood collection	0.19	0.33	0.42	0.27	0.15	0.16	0.20	0.28
Agriculture	0.72	0.59	0.44	0.66	0.81	0.65	0.74	0.49
Off-farm employment	0.09	0.08	0.15	0.07	0.04	0.19	0.07	0.24

There are different possible explanations for the observed increases in agricultural and fuelwood collection time over 2004–2011. Ethiopia has experienced high deforestation rates over the last four decades. This has contributed to increasing fuelwood scarcity that likely increases fuelwood collection time, particularly for households that collect it from communal areas. Ethiopia has also scaled up cooperative forest management efforts over the last decade that may have resulted in reduced access to forest resources among non-participant households. The trend may also reflect underreported fuelwood and agricultural labour time in the base year. Fuelwood collection time was not available from the base year survey, although that data contained detailed information on household time allocation for children under 21 that included farming activities, domestic work, and study time at home. Domestic time allocation was used as a proxy for fuelwood collection time. Another problem was that in the base survey ensete, which is the main staple food in Addado, was mistakenly identified as a tree (excluded from agricultural labour). In the 2011 survey effort detailed data on household labour time use were collected in order to correct these omissions in the base survey data.

Household access to energy and markets are important determinants of household energy use. Descriptive statistics of household expenditures are depicted in Figure 2.4 and Figure 2.5. There was a significant rise in the percentage share of non-food goods among household expenditures. Food expenditure budget shares dropped significantly in Basona Worena, from 58% to about 11%, and also declined in Addado by about 5%. The share of food expenditure among households in Udee and Trirufe exhibited an increase of about 9% and 1% respectively over the 2004–2011 period. A significant rise in non-food expenditures reflects changes due to expanded access to education and electricity, as well as urbanization of the study sites. In Basona Worena the mean expenditure share of kerosene increased from 3% to 21% over 2004–2011, but the shares of kerosene declined by about 7%, 6%, and 4% in Addado, Udee and Trirufe respectively. The main reason for this disparity is likely the electrification of the latter three villages, where households shifted to electricity as a substitute for kerosene for illumination purposes. This led to significant reductions in the percentages of households that purchased kerosene; by 31% in Udee, by 61% in Trirufe, and by 31% in Addado. In 2011 Trirufe had the highest percentage (80%) of households with access to electricity, followed by Udee (60%), and Addado (47%).

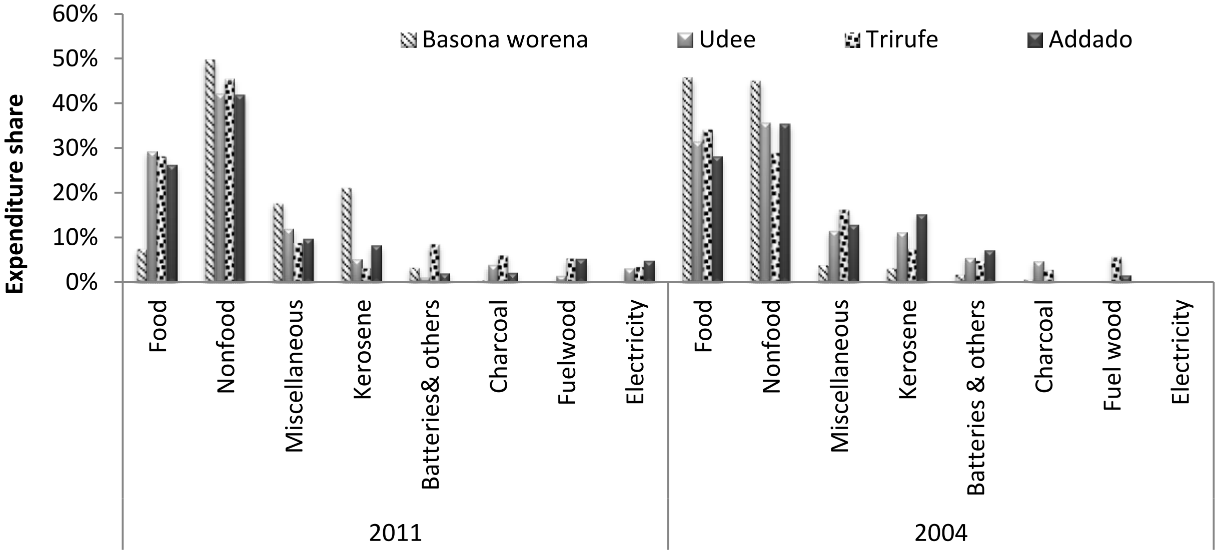

Figure 2.4. **Expenditure shares by category, village, and year among Ethiopian sample households**

Charcoal was purchased by at least some households in all villages. Approximately 14.5% of all sample households reported purchasing charcoal. Charcoal was purchased by nearly half of the households in Udee in 2004, but that percentage declined to about 34% in 2011, but the budget share of charcoal increased from 4% to about 8% over same period. Households in Udee spent a lower budget share on charcoal, which accounted for about 5% in 2004 and 1% in 2011. A large proportion (19%) of the households in Addado shifted to fuelwood over time, though the budget share of this fuel was insignificant (2%) (Table 2.4).

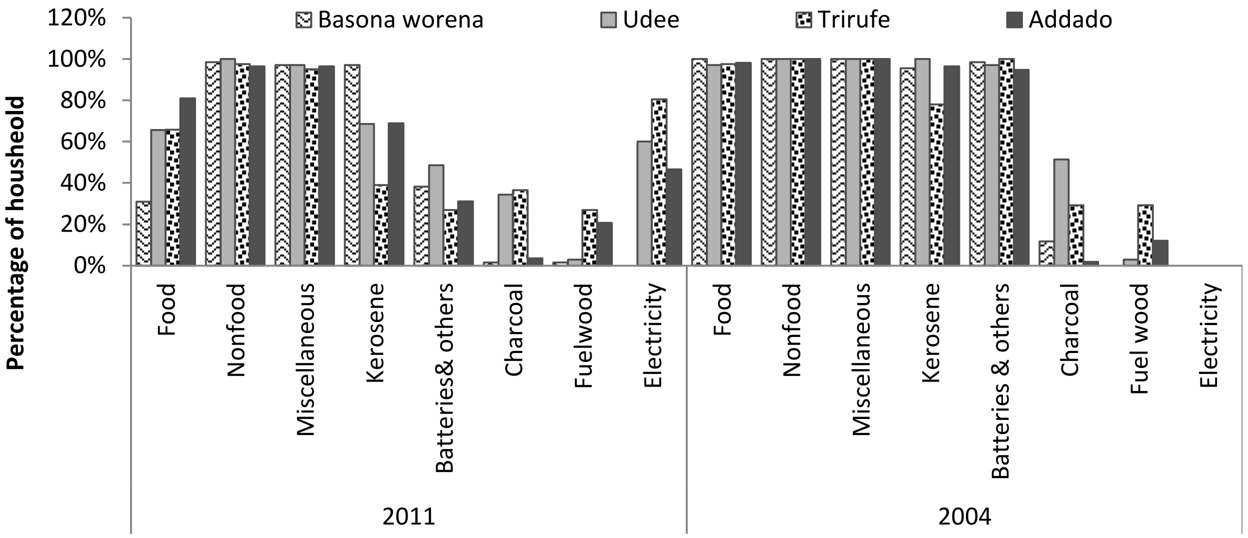

Figure 2.5. **Expenditure category percentages by village, and year among Ethiopian sample households**

Previous research indicated a clear dichotomy in household energy expenditure patterns between the poor and relatively wealthy households in rural Ethiopia (Guta, 2012a). Figure 2.6 and Figure 2.7 present monthly per capita household biomass (fuelwood and charcoal) and modern energy option expenditures. Total per capita household energy expenditures are described in Figure 2.8.[4] Among households that purchased fuelwood and charcoal, per capita expenditures on fuelwood were higher for wealthier households in 2004. Higher per capita expenditures on fuelwood in 2011 were likely due to household purchases of entire standing trees that are subsequently processed into fuelwood. Low-income households comprised 86% of the sample in 2004 and 83% in 2011. These households spent an average of about 3.00 ETB (US 0.24) per month on fuelwood over both periods, however, monthly per capita charcoal expenditures by low-income households rose from 2.70 ETB (US$ 0.31) in 2004 to about 4.90 ETB (US$ 0.57) in 2011. Per capita expenditures on modern energy options by the low-income households remained relatively stable over time. Monthly per capita kerosene expenditures increased from 1.85 ETB (US$ 0.21) to 2.00 ETB (US$ 0.23) over 2004–2011. Compared to their wealthier and middle-income counterparts, low-income households spent relatively more on battery operated lighting and other energy options. Mean monthly per capita overall energy expenditures by low-income households showed no change over time, remaining at about 3.30 ETB (US$ 0.38) for both periods.

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[4] The exchange rate was approximately US$1.00 = 8.63 ETB in 2004. The same exchange rate was used to compute real per capita expenditures in 2011.

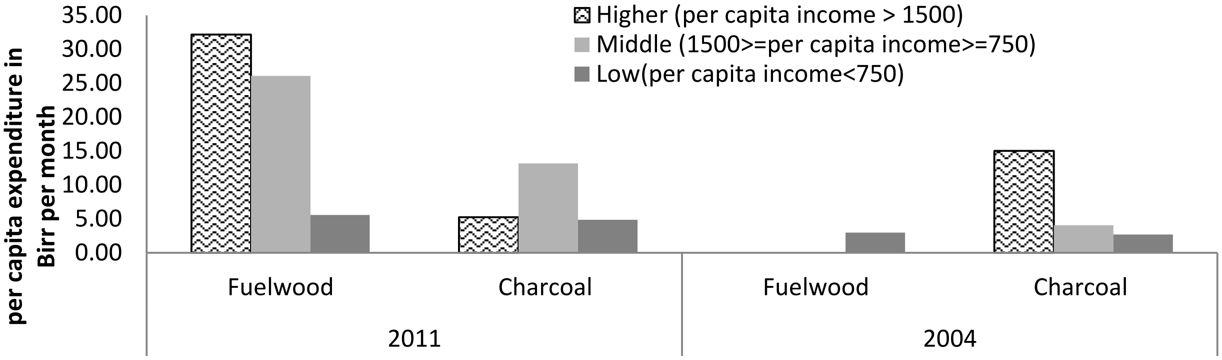

Figure 2.6. **Mean monthly per capita expenditures on biomass energy by energy type, income group, and year among Ethiopian sample households**

Mean per capita household expenditures on fuelwood and charcoal among the wealthier households rose significantly over time. This group comprised only 1.4% of the sample households in 2004 and 2.3% in 2011. Mean monthly per capita charcoal expenditures by wealthier households rose from 4.00 ETB (US$ 0.46) in 2004 to about 13.00 ETB (US$ 1.51) in 2011. Wealthier households did not report fuelwood purchases in 2004. The mean monthly per capita fuelwood expenditures by wealthier households in 2011 were about 32.00 ETB (US $3.71), however, monthly per capita expenditures on charcoal by these groups declined sharply from 15.00 ETB (US$ 1.74) to 5.30 ETB (US$ 0.17). Wealthier households also reduced per capita expenditures on kerosene. This is likely attributable to the substitution of electricity for kerosene. Compared to other households, wealthier households spent less on battery powered lighting and other fuels. Overall the monthly per capita expenditures by the wealthiest households increased slightly, from 14.60 ETB (US$1.69) to about 16.50 ETB (US$1.91) over the study period.

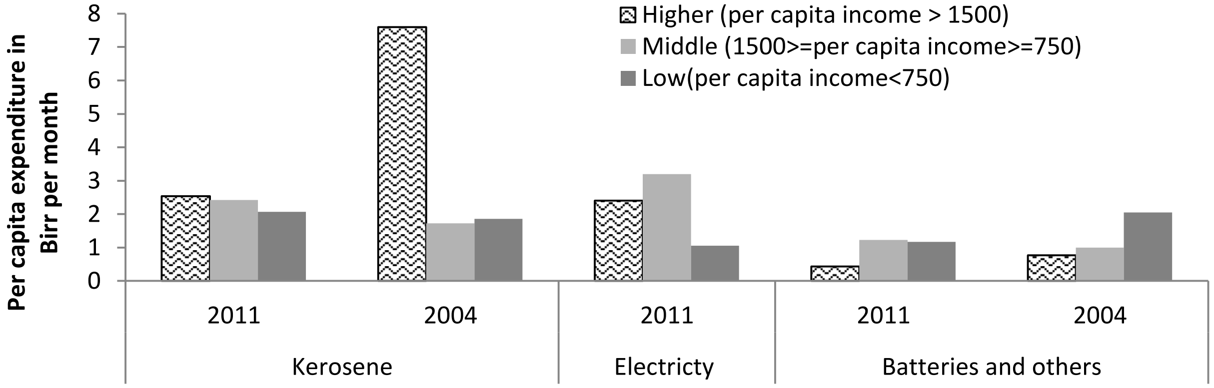

Figure 2.7. Mean monthly per capita household expenditures on modern energy options by energy type, income group, and year

The middle-income group comprised about 9.8% of the sample households in 2004 and 14% in 2011. Middle-income household per capita expenditures on fuelwood rose over time. Like the wealthier household group the middle-income group did not report fuelwood purchases in 2004. Mean monthly per capita expenditures on fuelwood by the middle-income group were about 26.00 ETB (US$ 3.01) in 2011. Similarly the monthly per capita charcoal expenditures by the middle-income group rose from about 4.00 ETB (US$ 0.46) to about 13.00 ETB (US$ 1.51). The monthly per capita electricity expenditures were the highest (3.20 ETB) for the middle-income group, followed by the wealthier (2.40 ETB or US$ 0.28) and poorer (1.00 ETB or US$ 0.12) households. Overall monthly per capita expenditures by the middle-income group more than doubled, from about 3.50 ETB (US$ 0.41) in 2004 to about 9.60 ETB (US$ 1.11) in 2011.

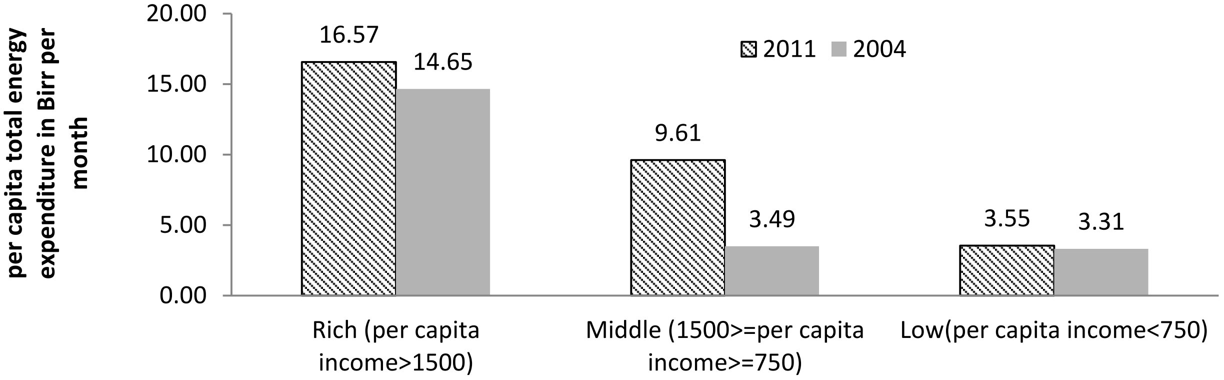

Figure 2.8. **Mean total monthly per capita expenditures by year and income group among Ethiopian sample households**

The descriptive statistics of the variables used in the analyses are presented in Table 2.6. Agriculture accounted for about 68% of the household labour in 2004 and declined to about 62% in 2011. The labour share of fuel collection increased from 19% to 28% over the same period. Although the number of off-farm employment labour hours increased, the relative share declined by 3%. This may also reflect an improvement in education in the selected villages. For instance, the share of family members that attended formal school increased from 23% to about 61% over 2004–2011, and the number of years of school completed by the household head also increased slightly. On average, the highest number of years of school completed by a family member increased from four to seven. Furthermore, the percentage of household heads with formal education increased from 9% to 13%. The share of household family members with formal education increased from 12% to about 36%. There were also slight declines in livestock quantity and parcel sizes, presumably due to population pressure and declining resources per capita.

Table 2.6. **Descriptive statistics of the household variables used in the analyses**

	2004		2011	
Variables	Mean	Std. dev.	Mean	Std. dev.
HH fuelwood collection labour time in hours per year	144.5	110.47	491.56	356.68
HH agriculture labour time in hours per year	902.4	1006	1252	780
HH off-farm labour time in hours per year	159.5	385	202	553
Fuelwood collection share of HH labour time	0.19	0.18	0.28	0.20
Agricultural share of HH labour time	0.68	0.26	0.62	0.22
Off-farm share of HH labour time	0.12	0.23	0.09	0.15
Monthly per capita HH food expenditures in ETB (100s)	3.63	3.42	6.27	1.68
Monthly per capita HH biomass energy expenditures in ETB (100s)	1.52	2.71	1.25	2.31

Variables	2004 Mean	2004 Std. dev.	2011 Mean	2011 Std. dev.
Monthly per capita HH kerosene expenditures in ETB (100s)	3.87	2.30	4.34	1.39
ℓn monthly HH electricity expenditures in ETB (100s)	0	0	0.54	1.62
ℓn hourly HH fuelwood collection labour wage in ETB (100s)	1.85	1.76	1.64	1.64
ℓn hourly HH agriculture labour wage in ETB (100s)	4.98	0.51	4.48	0.50
ℓn hourly HH off-farm labour wage in ETB (100s)	1.67	2.43	3.39	2.53
Remittance (dummy)	0.17	0.38	0.18	0.38
HH family size	6.07	2.48	5.38	2.12
Age of HH head	51.21	14.93	54.04	14.64
HH head education above elementary school (dummy)	0.09	0.29	0.13	0.33
HH member education high school or above (dummy)	0.12	0.32	0.36	0.48
Highest HH member education level in years	4.06	3.54	7.02	3.94
ℓn HH land area in hectares	0.56	0.72	0.35	0.73
ℓn number of HH trees	2.77	2.46	3.84	2.81
ℓn number of HH livestock (in TLU)	0.87	1.40	0.73	1.52
Ratio of HH dependents to labourers	1.33	1.01	0.69	0.68
Female share of HH workforce	0.48	0.24	0.49	0.25
Distance of village to nearest paved road in km	3.28	1.11	2.84	1.42
ℓn mean annual per capita village income (PCI) in ETB(100s)	5.84	0.34	6.05	0.22
Agricultural cooperative (dummy)	0.91	0.29	0.86	0.34
Agr. coop. * ℓn mean annual village PCI in ETB (100s)	18.91	5.49	16.84	7.73
ℓn mean village PCI * distance to nearest paved road	3.00	1.47	2.40	1.65
Agr. coop. * distance to nearest paved road	5.26	1.72	5.23	2.09
Inverse Mills ratio HH kerosene expenditures	0.42	0.42	0.13	0.14
Inverse Mills ratio HH food expenditures	0.29	0.22	0.03	0.11
Inverse Mills ratio HH biomass fuel expenditures	0.04	0.10	0.18	0.10
Inverse Mills ratio HH off-farm employment participation	0.59	0.35	1.18	0.41
Inverse Mills ratio HH biomass sales	1.44	1.14	2.47	2.72

Note: HH = household

2.5.Regression results and discussion

2.5.1. Probit model of household livelihood activity choices

Household decisions to allocate labour to any activity are expected to depend on the expected returns on labour. The family labour allocation wage and bio-based energy shadow prices among sample households were not available from the data. Labour supply decisions are primarily influenced by the expected return on labour among the different lines of work. Energy choice is affected by shadow opportunity costs or prices and other socio-economic and external environmental factors such as population density.

Household labour allocation was not observable unless households reported participation in one of the activities. If households did not allocate labour to any of the activities it is likely because their shadow valuation was higher than the expected return or wage rate. Wages from activities such as fuelwood collection are not observable for the greater proportion of rural households. Imputing shadow wage based on market wages or ignoring non-participants creates bias. Hence, shadow wages and prices need to be predicted on the basis of observable household demographic characteristics, education, assets and village variables that influence household preferences and activity choice. There were different types of biomass traded by sample households such as timber, fuelwood, and dried cattle dung, but it was not possible to differentiate prices. Off-farm employment activities include off-farm wages and self-employment via small businesses, trades, mills, shops, or preparing and selling traditional drinks (*tella, katikal*).

The regression results from the probit model for household livelihood activity choice specified in Eq. (2.22) and Eq. (2.23) are presented in Table 2.7 and Table 2.8 respectively. The difference between the two probit models was the inclusion of the time differenced mean of all exogenous variables in the latter case. The estimated coefficient indicates that higher mean per capita village income and the distance of each village from the nearest paved road were associated with increased household participation in off-farm employment and biomass income generation. In contrast, the existence of a village level agricultural cooperative was associated with lower household participation in both off-farm employment and biomass income generation.

Table 2.7. Probit model results for household participation in livelihood activities (used for predicting the inverse Mills ratios used in the FE-2SLS model)

	Dependent variables are binary participation indicators for each activity			
	2011		2004	
Explanatory variables	Fuelwood	Off–farm	Fuelwood	Off–farm
Distance of village to nearest paved road	3.33***(0.48)	1.03**(0.43)	0.61***(0.17)	–0.05(0.13)
ℓn per capita mean village income	25.33***(3.48)	7.19**(2.90)	4.24***(0.68)	0.52(0.56)
Agricultural cooperative (dummy)	–1.33(***0.40)	–0.58*(0.32)	–0.10(0.41)	0.49(0.41)
Remittance (dummy)	0.44(0.32)	–0.10(0.25)	–0.12(0.32)	0.33(0.27)
HH family size	0.03(0.07)	0.03(0.06)	–0.04(0.06)	0.02(0.05)
Age of HH head	–0.02**(0.01)	–0.02***(0.01)	–0.01(0.01)	–0.01(0.01)
HH head education above elementary	–0.95**(0.42)	0.06(0.30)	–0.60(0.44)	0.11(0.39)
HH member education high school or above	0.11(0.38)	–0.01(0.32)	–0.32(0.49)	–0.29(0.35)
Highest HH member education level	0.02(0.04)	–0.05(0.04)	0.04(0.05)	0.06*(0.04)
ℓn HH land area	0.08(0.24)	0.24(0.16)	–0.21(0.21)	–0.58***(0.17)
ℓn number of HH trees	0.02(0.06)	0.04(0.04)	–0.05(0.06)	–0.06(0.05)
ℓn number of HH livestock	–0.25**(0.11)	0.01(0.09)	0.47***(0.13)	–0.02(0.10)
Ratio of HH dependents to labourers	0.18(0.20)	0.03(0.17)	0.02(0.14)	0.25**(0.11)
Female share of HH workforce	–1.05*(0.58)	0.00(0.41)	0.27(0.52)	–0.16(0.41)
Constant	–160.55***(22.2)	–44.54**(18.8)	–27.12***(4.6)	–3.57(3.7)
Wald chi^2 (14)	104.74	48.81	111.27	33.17
Pseudo R^2	0.54	0.17	0.50	0.12
Log pseudo-likelihood	–65.97	–115.52	–70.79	–118.49

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01
Robust standard errors are reported in parentheses
HH = household

Table 2.8. Probit model results for household participation in livelihood activities (used for predicting the inverse Mills ratios for predicting wages used in the SUR and AIDS models)

	Dependent variables are binary participation in each activity for earnings			
	2011		2004	
Explanatory variables	Fuelwood	off–farm	Fuelwood	off–farm
Distance of village to nearest paved road	1.45(3.36)	7.34***(2.43)	26.82***(4.55)	9.54***(2.63)
ℓn mean per capita village income	33.34***(5.38)	6.06(3.96)	10.07***(1.41)	–0.73(0.71)
Agricultural cooperative (dummy)	–1.59***(0.45)	–0.59*(0.35)	–0.06(0.45)	0.12(0.45)
Remittance (dummy)	0.38(0.33)	–0.28(0.24)	–0.26(0.32)	0.24(0.30)
HH family size	–0.06(0.11)	0.19**(0.10)	–0.13(0.12)	–0.02(0.09)
Age of HH head	0.00(0.02)	0.00(0.02)	–0.06***(0.02)	–0.03(0.02)
HH head education above elementary	0.31(0.74)	0.51(0.56)	–2.21**(1.02)	0.60(0.58)
HH member education high school or above	–0.02(0.69)	0.28(0.54)	0.11(078)	–0.22(0.52)
Highest HH member education level	0.04(0.09)	–0.15**(0.06)	0.07(0.08)	0.11*(0.06)
ℓn HH land area	0.35(0.35)	0.41(0.26)	0.67*(0.37)	–0.38(0.27)
ℓn number of HH trees	0.07(0.10)	–0.01(0.09)	–0.06(0.08)	–0.04(0.06)
ℓn number of HH livestock	–0.05(0.17)	–0.04(0.13)	1.11***(0.34)	0.07(0.16)
Ratio of HH dependents to labourers	0.17(0.25)	–0.26(0.22)	–0.02(0.25)	0.28(0.22)
Female share of HH workforce	–0.43(0.71)	–0.33(0.57)	–0.48(0.60)	–0.81(0.57)
Constant	–213.06***(36.43)	–32.77(26.38)	–83.49(10.55)	–1.37(5.05)
Wald chi^2 (25)	136.38	71.56		61.41
Pseudo R^2	0.58	0.22	0.57	0.21
Log pseudo-likelihood	–60.50	–108.19	–60.62	–106.49

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01
Robust standard errors (SE) are reported in parentheses
The mean of all the exogenous variables were included but are not reported here
HH = household

2.5.2. Fuelwood scarcity, cross-wage effects, and their welfare implications

The relationship between labour allocated to an activity and shadow wage can be broken down into the substitution effect and the income effect as explained below. The findings indicate that both the own-shadow wage effects and cross-wage substitution effects were consistent with rational economic theory. The positive and statistically significant own-wage effect indicates that households most often allocated an increased share of labour time to activities that have a greater return on labour time.

The Slutsky decomposition results indicate that a positive substitution effect is straightforward. This is because with increases in fuelwood price it becomes more profitable for net fuelwood sellers to allocate more labour to fuelwood production. The same is true for net fuelwood buyers as they opt to allocate more labour to collection rather than pay higher market prices. The income or profit effect, however, depends on the relative demand for leisure and fuel, whether households are net buyers or sellers of fuel, whether fuel is a normal or inferior good, or whether relative household demand for leisure as compared to fuelwood increases with income. A good is considered normal if the demand for it rises with income. The income effect is expected to be negative if leisure demand outweighs demand for fuel as a result of increased income, but if the reverse is true it is positive. The empirical results indicate a positive overall own-wage effect for all activities. This is consistent with theory and depends on two conditions: first, if the income/profit effect is positive in addition to the substitution effect, and second, if the positive substitution effect dominates the negative effects of income/profit arising from wage changes. There are two principal conditions that allow a positive income effect to materialize. One condition is if households are self-sufficient or are net sellers of fuel, which means that households with surplus income use it to purchase food rather than fuel. Since, most rural Ethiopian households face food security challenges the demand for fuel is normally expected to dominate demand for leisure. This is because households prefer to purchase food as income increases and to collect fuel, which is an input to cooking that requires cheaper labour provided by women and children, and they are less likely to increase leisure demand. The majority of households also lack access to modern energy alternatives to fuelwood and spend greater effort on fuel collection than leisure as the utilitarian value and return on fuelwood is a complement to food security and other needs.

The cross wage or substitution effects are examined for substitution to determine whether there was competition or complementarity between fuel collection and food security. The cross-wage or substitution effect is how increasing returns of one activity impact the labour share of other activities. At the household scale the substitution or complementarity between biomass energy and agriculture or food production depends on various conditions discussed below. It is often difficult to predetermine the effect because of the non-separable nature of household labour supply.

First, from the perspective of poor peasant households facing chronic food security challenges, if forest access is open then households are expected to respond to increases in food price by allocating more labour to fuel extraction to generate income for the purchase of food. Recently Ethiopia has been implementing cooperative forest management initiatives, which might have resulted in restricted access to forests. These determine rights regarding the collection of fuel, fodder, timber, and other forest products on the basis of pre-determined regulations and predefined quotas. From this aspect, increases in food price may not always be accompanied by increased fuel collection labour allocation. Access to forest and forest governance policies, thus, play crucial roles as cooperative forest use policies and regulations may preclude open access and the ability of households to increase labour allocated to forest exploitation.

Second, the decision of whether to use agricultural waste for energy, soil fertility management, livestock fodder, or income generation is another factor. With increased food prices net food buyers may increasingly depend on income from the sale of agricultural fuels to support their food budget, or they may allocate greater labour or crop residues to increase food production rather than purchase food. For instance, almost all households in Basona Worena and a few households in Udee sold cattle dung. For net food sellers, higher food prices may motivate households to use more agricultural waste as organic fertilizer in order to improve food production. Household sales of crop residues and cattle dung and their use to improve food production lead to trade-offs with the use of these resources for energy and their value as a substitute for fuelwood. The sale of agricultural waste for fuel is expected to increase household fuel collection labour allocation. Higher agricultural shadow wages mean that more labour would be allocated to agriculture that in turn increases agricultural fuel production. Agricultural fuels can potentially substitute fuelwood from forests, and thus reduce fuel collection labour shares. As a result, the net effect appears to be indeterminate.

2.5.2.1. Household labour allocation by activities

The estimated coefficients from the FE-2SLS model corrected for selectivity of participation in fuelwood and off-farm activities, and endogeneity of wages are presented in Table 2.9. The estimated instrumental variable coefficients were statistically significant for fuelwood collection labour allocation. The tests statistics for the validity of instruments are reported at the bottom of the table. The tests statistics support the validity of the instruments. The Angrist-Pischke statistics for each of the first-stage wage equations were statistically significant for all of the labour supply models. Both Cragg-Donald and Anderson canon test results supported the rejection of weak and under identification in all of the labour supply estimates. According to the Hansen-Sargan test results for the over-identification of instruments the null hypothesis of zero correlation between the instruments and the error term cannot be rejected.

The first stage results for the instrumented wage are also presented in Table 2.9. The mean per capita village level income and the distance of a village from the nearest paved road reduce fuelwood shadow wage, and both exhibit statistically significant and plausible relationships. The villages with wealthier residents exhibited greater dependence on fuelwood, suggesting that fuelwood is a normal good (Guta, 2012). Greater fuelwood scarcity was reflected by lower fuelwood shadow wages. The greater the distance of a village from the nearest paved road, the lower the shadow wage, as labour markets are highly constrained. This explanation also holds for off-farm employment. The mean per capita village level income increased with off-farm and agricultural wages, although it was significant in the former case due to constrained rural off-farm labour markets. Households in wealthier villages had greater opportunity to find off-farm employment with higher wages. These households may also have had greater access to agricultural technology options, and therefore peer learning effects may be higher in these villages because wealthier households have greater potential to adopt improved agricultural practices or technologies and relatively poorer households may have increased opportunities to learn from their wealthier counterparts.

Table 2.9. FE-2SLS model regression results for annual household labour allocations, corrected for both endogenieity and selectivity

	Dependent variables (ℓn wages and ℓn labour time in hours per year)					
	First-stage wage equation[1]			Final stage labour equation		
Explanatory variables	Fuelwood	Agriculture	Off-farm	Fuelwood	Agriculture	Off-farm
ℓn HH fuelwood wage				–0.90	2.62***	–0.19
				(0.80)	(0.65)	(0.34)
ℓn HH agriculture wage				–4.88***	–1.55	0.791
				(1.88)	(1.53)	(0.80)
ℓn HH off-farm wage				–0.36	–0.66***	0.99***
				(0.28)	(0.23)	(0.12)
Remittance (dummy)	0.02	0.04	–0.88*	0.42	–0.79*	0.07
	(0.05)	(0.05)	(0.47)	(0.51)	(0.42)	(0.22)
HH family size	0.00	0.00	0.12	0.05	0.15*	0.07*
	(0.01)	(0.01)	(0.10)	(0.10)	(0.08)	(0.04)
Age of HH head	–0.04***	–0.01***	0.02	–0.11**	0.10**	–0.01
	(0.00)	(0.00)	(0.02)	(0.05)	(0.04)	(0.03)
HH head education above elementary	–0.09	0.52***	0.87	3.00***	1.81**	–0.78
	(0.07)	(0.07)	(0.65)	(1.12)	(0.91)	(0.48)
HH member education high school or above	0.01	0.36***	0.61	1.91**	0.75	–0.50
	(0.06)	(0.06)	(0.54)	(0.82)	(0.66)	(0.35)
Highest HH member education level	0.00	–0.08***	–0.03	–0.36**	–0.12	0.08
	(0.01)	(0.01)	(0.07)	(0.16)	(0.13)	(0.07)
ℓn HH land area	–0.01	0.10***	0.24	0.64**	0.257	–0.26**
	(0.03)	(0.03)	(0.32)	(0.30)	(0.25)	(0.13)
ℓn number of HH trees	–0.04***	–0.05***	0.10	–0.15	0.121	0.07
	(0.01)	(0.01)	(0.08)	(0.14)	(0.11)	(0.06)
ℓn number of HH livestock	0.19***	0.16***	–0.24	0.86**	–0.46	0.05
	(0.02)	(0.02)	(0.22)	(0.43)	(0.35)	(0.19)
Ratio of HH dependents to labourers	0.13***	0.06**	–0.37	0.23	–0.42*	–0.04
	(0.02)	(0.03)	(0.24)	(0.31)	(0.25)	(0.13)
Female share of HH workforce	0.00	0.04	–0.54	0.59	–0.27	–0.08
	(0.06)	(0.06)	(0.61)	(0.58)	(0.47)	(0.25)
Inverse Mills HH fuelwood	–0.16***	0.07***	–0.56**	–0.25*	0.046	–0.02
	(0.02)	(0.03)	(0.22)	(0.13)	(0.11)	(0.06)
Inverse Mills HH off-farm	0.22***	0.03	–2.97***	–0.63	–1.77**	0.15
	(0.06)	(0.06)	(0.58)	(0.92)	(0.75)	(0.39)
Distance of village to nearest paved road	–8.57***	4.21***	–2.42			
	(1.11)	(1.15)	(10.85)			
ℓn mean per capita village income	–5.68***	2.75**	4.55			
	(1.27)	(1.30)	(12.33)			
Agricultural cooperative (dummy)	–6.42	1.73	56.76			
	(7.00)	(7.20)	(68.15)			
Dummy agr. coop. * ℓn mean village PCI	0.87	–0.41	–9.14			
	(1.11)	(1.14)	(10.78)			
ℓn mean village PCI * village distance to nearest paved road	1.29***	–0.61***	0.58			
	(0.16)	(0.17)	(1.57)			
Agr. coop. * village distance to nearest paved road	0.33	0.07	–0.42			
	(0.17)	(0.18)	(1.68)			
Number of observations	428	428	428	428	428	428
F (19, 195)	56.92	48.28	7.44			
R^2	0.85	0.82	0.42			
F (18, 196)				3.23(0.00)	2.57(0.00)	47.11(0.00)

Explanatory variables	First-stage wage equation[1]			Final stage labour equation		
	Fuelwood	Agriculture	Off-farm	Fuelwood	Agriculture	Off-farm
Angrist-Pischke F-test	30.18 (0.00***)	5.20 (0.00***)	2.57 (0.04**)			
Anderson canon. corr. LM statistic (p-value)				9.57 (0.048**)	9.57 (0.048**)	9.57 (0.048**)
Cragg-Donald F-statistic				1.52	1.55	1.52
Sargan statistics (p-value)				2.17 (0.54)	2.08 (0.56)	0.100 (0.99)

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01
[1] First stage in fuelwood labour equation
HH = household

The impact of shadow wages on labour supply was examined using the estimated coefficients. These coefficients reveal that an increase in fuelwood labour shadow wage would lead to a statistically significant increase in agriculture labour supply, which is consistent with the research hypothesis. This reflects a positive welfare effect among households with access to forest biomass. The result indicates that an increase in fuelwood shadow wage (better access to forest biomass) results in an increase in labour time used for agriculture with wage elasticity of +2.62, indicating that a 1% increase in fuelwood shadow wage was associated with an increase in agricultural labour of about 2.62%. This suggests that the greater the scarcity or lower the shadow wage, the lower the amount of labour that was allocated to agricultural production among sample households. Thus, fuelwood scarcity was found to divert labour to biomass fuel collection, which implies the existence of fuel-food trade-offs.

Another interesting result is the significant negative relationship of the shadow wage or marginal product (MP) of agriculture with fuelwood collection labour. There are two plausible explanations for this result. First, increases in agricultural productivity (wage) create greater opportunity for the generation of agricultural fuels (dried cattle dung and crop residues), which are complementary to fuelwood consumption.

Many households in the sample used agricultural residue fuels to cope with fuelwood scarcity. These energy alternatives are readily available from agricultural activities and require little or no additional labour effort. Second, increases in agricultural wage relate to increases in household disposable income, which can be used to purchase energy. When both selectivity and endogeneity are controlled, a 1% increase in agricultural shadow wage or marginal product of labour in agriculture resulted in a 4.88% decline in labour allocated to fuelwood collection. This conforms to the findings of Shivery and Martinez (2001), which associated agricultural intensification with reduced labour for forest extraction activities.

2.5.2.2. Household joint labour allocation to livelihood activities

The wages earned by a household from one activity not only affect the labour allocated to that activity, but also the amount of labour allocated to alternative activities. This suggests the need for a joint analysis household labour supply model. Labour allocation for the three activities was estimated jointly using a SUR model. Moreover labour shares of the three activities were estimated jointly using an AIDS model. As explained earlier, the FE was controlled by incorporating the Mulduk approach. For these purposes the shadow wages were predicted from the first-stage wage equation based on Eq. (24) and using the predicted inverse Mills ratios for fuelwood and off-farm given in Table 2.8.

The means of the excluded instrumental variables and all the exogenous variables were calculated for the analyses but are not reported. The estimated coefficients of the first-stage wage equations are depicted in Table 2.10. The selectivity test results for both fuelwood collection and off-farm employment were statistically significant at 1%, proving that selectivity was a problem. The estimated coefficients of mean per capita village level income and the distance of villages from the nearest paved roads reduced fuelwood shadow wage and were statistically significant at 1%.

Table 2.10. Shadow wage estimates by household livelihood activity based on Wooldridge (1995) panel data, corrected for selectivity

	Dependent variables (ℓn labour time in hours/year)		
Explanatory variables	Fuelwood collection labour	Agricultural labour	Off-farm labour
Distance of village to nearest paved road	–14.88***(0.63)	–0.93** (0.38)	6.91 (5.36)
ℓn mean per capita village income	–7.02***(0.80)	–0.11(0.68)	–37.16 ***(9.67)
Agricultural cooperative (dummy)	1.86(4.40)	0.05(4.57)	–252.41*** (61.49)
Dummy agr. coop. * ℓn mean village PCI	–0.41(0.67)	–0.05(0.68)	38.18*** (9.36)
ℓn mean village PCI * village distance to nearest paved road	2.20***(0.08)	0.12***(0.05)	–1.93*** (0.65)
Agr. coop. * distance to nearest paved road	0.12(0.13)	–0.01(0.15)	7.76***(1.81)
Remittances (dummy)	–0.02(0.04)	0.02(0.04)	–0.31(0.47)
HH family size	0.00(0.01)	0.01(0.01)	0.00(0.10)
Age of HH head	–0.04***(0.00)	–0.01***(0.00)	0.01(0.02)
HH head education above elementary	–0.01(0.09)	0.60***(0.06)	0.24(0.69)
HH Member education high school or above	0.04(0.06)	0.39***(0.04)	0.18(0.53)
Highest HH member education level	0.00(0.01)	–0.08***(0.01)	0.03(0.07)
ℓn HH land area	0.00(0.03)	0.08***(0.02)	–0.49(0.30)
ℓn number of HH trees	–0.02***(0.01)	–0.04***(0.01)	0.04(0.08)
ℓn number of HH livestock	0.15***(0.03)	0.15***(0.01)	0.09(0.19)
Ratio of HH dependents to labourers	0.09***(0.02)	0.05***(0.02)	0.33(0.23)
Female share of HH workforce	0.03(0.07)	0.05(0.06)	–0.29(0.63)
Year 2011 (dummy)	–0.26***(0.02)		
Inverse Mills ratio HH fuelwood			–0.65***(0.18)
Inverse Mills ratio HH off-farm	–0.74***(0.06)	–0.39***(0.05)	3.54***(0.76)
Constant	–10.08(6.28)	24.68***(4.83)	216.97***(68.34)
Number of observations	414	428	428
R^2	0.98	0.90	0.26
F (33, 394)	1342	133	7.88

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01

Robust standard errors (SE) are reported in parentheses
The dependent variables are the log of the wages of each activity
The fixed effect was controlled using the Mulduk approach
HH = household

The estimated coefficients of the final SUR model are reported in Table 2.11. The signs of the own-wage effects, cross-wage effects, and other explanatory variables can be compared and contrasted, but not their magnitudes. This is because unlike the FE-2SLS model, the SUR model included the means of all dependent variables except wages.

The estimated coefficients indicate that the cross-wage effect between fuelwood and agricultural labour allocation have the same relationships (signs) as the results of the FE-2SLS model. The estimated coefficients from both the SUR and FE-2SLS model results indicate that with increases in fuelwood labour, wage households increase the amount of labour allocated to fuelwood collection. This suggests that increases in household access to biomass reduce the amount of labour required to collect it.

Table 2.11. SUR model regression results for household joint labour allocation

	Dependent variables (ℓn labour time in hours/year)		
Explanatory variables	Fuelwood collection labour	Agricultural labour	Off-farm labour
ℓn HH fuelwood wage[a]	–0.31***(0.11)	0.14**(0.06)	–0.26(0.18)
ℓn HH agricultural wage[a]	–0.61**(0.28)	–0.34**(0.16)	–0.17(0.46)
ℓn HH off-farm wage [a]	–0.20**(0.09)	0.03(0.05)	0.94***(0.15)
ℓn total HH labour time	0.07(0.20)	–0.18(0.12)	–0.06(0.33)
Remittances (dummy)	0.00(0.07)	0.06(0.04)	0.09(0.11)
HH family size	–0.05***(0.01)	0.01(0.01)	–0.02(0.02)
Age of HH head	0.46(0.43)	0.11(0.25)	–0.17(0.71)
HH head education above elementary	0.15(0.24)	–0.34**(0.14)	0.01(0.40)
HH Member education high school or above	–0.01(0.04)	–0.02(0.03)	–0.01(0.07)
Highest HH member education level	0.11(0.18)	0.35***(0.10)	–0.10(0.30)
ℓn HH land area	0.04(0.04)	–0.01(0.02)	0.00(0.06)
ℓn number of HH trees	0.16*(0.10)	0.00(0.06)	0.12(0.16)
ℓn number of HH livestock	0.08(0.15)	–0.04(0.09)	–0.01(0.25)
Ratio of HH dependents to labourers	0.26(0.29)	–0.07(0.17)	–0.01(0.49)
Female share of HH workforce	1.33***(0.27)	0.76***(0.16)	–0.32(0.44)
Year 2011 (dummy)	–0.13**(0.06)	0.08**(0.03)	–0.12(0.10)
Inverse Mills ratio HH fuelwood	0.03(0.06)	–0.07**(0.04)	–0.02(0.10)
Inverse Mills ratio HH off-farm	8.01***(1.50)	6.31***(0.87)	1.63(2.49)
Constant	–0.31***(0.11)	0.14**(0.06)	–0.26(0.18)
Number of observations	428	428	428
R^2	0.23	0.40	0.21
chi^2	127.68	288.11	114.67

Note: * P < 0 .1, ** P < 0.05, *** P < 0.01
[a] Predicted wages from the model are presented in Table 2.10
The means of excluded instrumental variables and all exogenous variables were included in the analyses but are not reported here
HH = household

2.5.2.3. Household joint labour share allocation to livelihood activities

The estimated coefficients from the joint AIDS labour share equations are presented in Table 2.12. Tests were conducted for each of the variables if the parameters satisfied key model assumptions (i.e. the adding-up, homogeneity, and Slutsky symmetry conditions). The symmetry condition, which states that cross-wage effects are equivalent, was immediately inferred from the model results. The adding-up restriction test was computed from the model results. A likelihood ratio (LR) test result for the three systems of share equations was 311, indicating that the results were statistically significant at 1%. Hence, the null hypothesis for the adding-up restriction was not rejected. A Wald χ^2 test was used to test for homogeneity of the various demographic and other explanatory factors included in the model. The χ^2 test results were statistically significant for household size, age of household head, household head education above the elementary level, land parcel size, the inverse Mills ratio for fuelwood, and the year 2011. For these variables the joint null hypothesis of homogeneity was rejected. This means that these variables had statistically significantly associations with the joint labour shares. For the remaining variables incorporated into the model (the age of the household head, the highest education level achieved by a family member, and the dependency ratio), however, the χ^2 test results were not statistically significant, indicating that the joint null hypothesis of homogeneity could not be rejected.

Table 2.12. Almost Ideal Demand System model estimates of the household joint labour share equations

Explanatory variables	Dependent variables (labour share)		
	Fuelwood labour share	Agriculture labour share	Off-farm labour share
ℓn HH fuelwood wage[a]	0.127**(0.042)		
ℓn HH agricultural wage[a]	–0.088**(0.041)	0.083*(0.046)	
ℓn HH off-farm wage[a]	–0.039**(0.018)	0.004(0.018)	0.034***(0.010)
ℓn total HH labour time	–0.074***(0.009)	0.073***(0.010)	0.001(0.009)
Remittance (dummy)	–0.001***(0.001)	0.001(0.001)	–0.001(0.001)
HH family size	0.001***(2.30E-04)	–4.05E-04(2.8E-04)	–2.7E-04(2.47E-04)
Age of HH head	1.01E-04**(4.8E-05)	–1.76E-04***(6.0E-05)	7.49E-05(5.07E-05)
HH head education above elementary	–0.005**(0.002)	0.004*(0.002)	0.001(0.001)
HH member education high school or above	2.44E-04(0.001)	–0.001(0.002)	0.001(0.001)
Highest HH member education level	–1.80E-04(1.55E-04)	2.72E-04(1.97E-04)	–9.16E-05(1.7E-04)
ℓn HH land area	4.4E-04(0.001)	–0.002**(0.001)	0.001**(0.001)
ℓn number of HH trees	1.10E-04(1.7E-04)	1.99E-04(2.1E-04)	–3.09E-04*(1.8E-04)
ℓn number of HH livestock	3.74E-04(3.33E-04)	1.45E-04(4.19E-04)	–0.001(3.63E-04)
Ratio of HH dependents to labourers	–0.001(0.001)	0.000(0.001)	4.73E-04(0.001)
Female share of HH workforce	-2.13E-04(0.001)	0.001(0.002)	–0.001(0.002)
Inverse Mills ratio HH fuelwood	3.11E-04*(1.79E-04)	–0.001***(2.2E-04)	0.001***(1.9E-04)
Inverse Mills ratio HH off-farm	–0.001**(2.32E-04)	4.71E-04***(2.9E-04)	3.86E-05(2.4E-04)
Year 2011 (dummy)	–0.006***(0.001)	0.002(0.001)	0.004(0.001)
Constant	–1.691****(0.0237)	2.456***(0.265)	0.235(0.220)
Predicted HH labour share	0.24	0.65	0.11
Number of observations	428	428	428

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01

Log-likelihood for overall significance of the model is 320.94
[a] Predicted wages from the model are presented in Table 2.10
The dependent variables are the labour shares of the respective activities
The instrumental variables and their means were excluded from the labour share equation, the means of all of the exogenous variables were included in the analyses but are not reported here
HH = household

The fuel collection labour share had a significant positive association with its own wage. The positive own-wage effect is consistent with rational household behaviour, which predicts that households respond positively to increasing returns by allocating a greater labour share by either withholding or diverting labour allocated to competing activities or reducing leisure time.

The model results indicate a theoretically consistent cross-wage effect of off-farm employment on household labour allocation to fuel collection. There were negative cross-wage effects among all three activities as expected. Agricultural labour supply was negatively correlated with the shadow wage of fuelwood (5%) and vice versa (Table 2.12). Fuelwood labour supply was also negatively correlated to off-farm wage.

It is important to understand the sensitivity of the labour supply for a particular activity to its shadow wage and changes in wages from other activities. The wage elasticity of labour was calculated based on the Slutsky wage elasticity of labour allocations for each activity and the elasticity of substitution wages computed from the regression parameters and the mean predicted labour shares reported at the bottom of Table 2.12. Wage elasticity values were computed from the labour share model results. The coefficients of the predicted shadow wage in the system regression equation shown in Table 2.12 can be rewritten as:

$$\frac{\partial l_i}{\partial \ell n(w_i)} = \left(\frac{\partial l_i}{\partial w_i)}\right) w_i \;\cong\; \eta_{ii} \tag{2.34}$$

Own- and cross-wage elasticity equations were written respectively as:

$$\varepsilon_{ii} = \left(\frac{\partial l_i}{\partial w_i)}\right)\frac{w_i}{l_i{}'} = \frac{\gamma_{ii}}{l_i{}'} \tag{2.35}$$

$$\varepsilon_{ij} = \left(\frac{\partial l_i}{\partial w_{ij})}\right)\frac{w_{ij}}{l_i{}'} = \frac{\gamma_{ij}}{l_i{}'} \tag{2.36}$$

where ε_{ii} represents the own-wage elasticity of activity i, ε_{ij} and is the cross-wage elasticity of labour allocation between the wage of activity i and labour allocated to activity j, and vice versa.

The elasticity values are given in Table 2.13. A 1% wage increase would have a less than proportionate change in the labour share allocated to fuel collection (0.53%). A 1% increase in fuelwood shadow wage would result in a 0.14% decline in the agricultural labour share. With each 1% increase in off-farm wage the fuel collection labour allocations declined by 0.35%. Off-farm wage also provides financial support for the purchase of energy substitutes and food. The wage elasticity of the substitution of labour allocation depends on the nature of the subsistence economy, where there are limited employment opportunities. Households complement food security through agriculture, bartering labour for food, off-farm employment, and from collecting and selling fuel to purchase food.

Table 2.13. Own- and cross-wage elasticity of household labour shares among livelihood activities

	Predicted	Model parameters (γ_{ii}, γ_{ij})			Wage elasticity ($\varepsilon_{ii}, \varepsilon_{ij}$)		
Activity	share (l_i')	Fuelwood	Agriculture	Off-farm	Fuelwood	Agriculture	Off-farm
Fuelwood collection	0.24	0.127			**0.53**		
Agriculture	0.65	–0.088	0.083		**–0.14**	**0.13**	
Off-farm	0.11	–0.039	0.004	0.034	**–0.35**	0.04	**0.31**

2.5.2.4. Cross-wage effects and other determinants of household labour allocation and related empirical underpinnings

There are four potential conditions that could explain the negative relationships observed between fuelwood collection labour wage and labour allocated to agricultural activity. First, if the negative substitution effect of changes in shadow wage dominates any positive income/profit effects. Second, if a household is a net seller of non-fuel goods like food, and at the same time fuel is an inferior good. Third, if a household is a net seller of non-fuel goods, or if food and fuel are normal goods, but either income induced demand for leisure dominates demand for fuel or else the household purchases rather than sells fuel. Fourth, if fuel is a normal good and a household collects it rather than purchases it, but the household is a net buyer of non-fuel goods (including food). For Ethiopian households the first and the last conditions seem to be the most plausible explanations for the negative relationships. There could also be a number of other explanations. For instance, poor households are often concerned about food security. Hence, rather than switching labour from agriculture to fuel collection in the face of fuelwood scarcity, households may reduce leisure time, limit other domestic chores performed by women like preparing food, or withdraw children from school. These are implicit or indirect welfare effects of fuelwood scarcity and fuel vs. food trade-offs that can trap households in poverty and exacerbate gender inequalities.

The estimated negative cross-wage effect on fuelwood labour allocation of agricultural and off-farm wages obtained from all the econometric models applied in this study (FE-2SLS, SUR, and AIDS) is consistent with the results of empirical studies in other developing countries. Most related empirical studies have examined non-forest wage effects on the extraction of forest products. Increase in the expected wage from non-forest activities was negatively associated with forest exploitation among Malawian (Fisher et al., 2005), Philippine (Shively, 2001), Nepalese (Bluffstone, 1995), and Chinese households (Wang et al., 2012).

The finding also lends further support to the idea that off-farm wages may lead to reductions in fuelwood labour. However, in rural Ethiopia off-farm labour markets are extremely limited and private off-farm businesses are constrained by the lack of credit. Consequently farming households only rarely work off-farm and typically earn meagre wages when they do, which may not be a sufficient incentive for households to shift away from fuelwood collection. This may be also related to the limited availability of modern energy alternatives, to which households are more likely to switch with increases in off-farm income. In the literature the role of off-farm employment on energy substitution is also ambiguous. In rural China changes in rural livelihoods, specifically off-farm employment and agricultural intensification, contribute to household fuel substitution (Wang et al., 2012). Fuelwood collection is one of the major forest product uses in many countries. Off-farm employment diversifies livelihoods and results in decreased demand for agricultural labour. This effect decreases the importance of biomass energy and agriculture with increasing off-farm wages. Households may also shift to less labour intensive agricultural production (Shi et al., 2009). Off-farm employment may also enable households to adopt different agricultural technologies or methods that reduce demand for agricultural labour. Hence, policies that support initiatives such as micro-credit opportunities for creating self-employment or private businesses and investment in rural job creation may contribute to a broader shift in household energy consumption.

An empirical study from Nepal found that increased exposure to extra-household employment (i.e. in community organizations) stimulated fuel substitution (Macht et al., 2007). Off-farm employment and agricultural specialization were important determinants of household fuelwood substitution in an underdeveloped area in China (Wang et al., 2012). A study from India found that off-farm employment opportunities reduced fuelwood use (Baland et al., 2010). Several studies have also identified a number of policy options that improve rural livelihoods and promote fuel-switching from solid biomass to modern energy alternatives, such as: investment in rural infrastructure, investment in electricity infrastructure, facilitating improved market access in remote villages, and alternative income-generating activities (Chen et al., 2006; Baland et al., 2010; Lee, 2013). Policies that support initiatives such as micro-credit opportunities for creating self-employment or private businesses and investment in rural job creation, paralleled with sustainable energy provisions that support biogas, solar, micro-hydroelectric, or other modern energy alternatives can play crucial roles in addressing environmental concerns arising from forest overexploitation, alleviating poverty at the community and household scales, supporting ecosystem restoration, and ultimately helping to generate benefits and improve food security for the poor.

The estimated coefficients of household education variables yielded mixed results. Fuelwood labour declined with increases in the highest education level of a household member. Nonetheless, fuelwood labour increased for households with heads that had attained an education beyond elementary school and there was a positive association with fuelwood collection labour among households with at least one household member with a high school or above education. The mixed results may reflect the imperfections in markets for educated labour in rural areas.

Increases in household assets (land and livestock) were associated with increased labour allocation to fuelwood collection (Table 3). There are two explanations for this observation. First, empirical studies have found evidence that suggests that fuelwood is a normal good among Ethiopian households, and thus its consumption should increase with increases in household income and assets (Mekonnen, 1999; Guta, 2012). Second, as explained earlier this finding conforms with empirical studies on the complementarity of forest extraction activities with subsistence activities like cattle herding and livestock fodder collection in India (Dayal, 2006) and Namibia (Palmer and Macgrego, 2009).

2.5.3. Effects of fuelwood scarcity on household energy and food expenditures, and related energy mix and welfare implications

Household energy expenditures and preference for different fuel types and energy mixes are expected to be affected by the implicit shadow opportunity costs. Furthermore, agricultural and off-farm wages are expected to play important roles in determining household fuel choice. The analysis was extended to investigate the effects of shadow wages and other important socio-economic factors on household fuel choice and energy expenditures. This permitted the examination of how households respond to changes in the shadow wages in terms of their fuel choice behaviour.

Households were divided into four categories: households that purchased fuelwood and or charcoal with or without one or more modern energy options (kerosene, electricity, battery-powered lighting, etc.), households that used kerosene only, households that used electricity only, and households that mixed any of two or more of the modern energy options (Table 2.14). The household energy fuel compositions presented in Table 2.14 are based on the percentage shares of household fuel use. In 2004 about 70% of the households used a mix that included one or more of the modern energy options and about 25% of the households purchased biomass in combination with one or more modern alternatives. Only 5% of the households purchased battery-powered and other options, and only 1% purchased kerosene only. A significant decline was observed in the percentage of households that used a combination of one or more modern fuels in 2011. The percentage of households that used only kerosene rose from 1% to about 32%. This is likely attributable to the rising prices of kerosene, battery-powered devices, and other fuels, which particularly affects households without access to electricity. Access to electricity, which was established between the two data collection periods, likely accounted for the observed shift in household fuel choice. Although about 38% of the households had access to electricity in 2011, only 9% used it along with collected biomass energy. The remaining 29% of households combined electricity with one or more purchased fuels. In order to cope with electricity interruptions households used kerosene as a backup to electricity. Electricity is available in semi-urban areas where households often purchase charcoal and fuelwood.

Table 2.14. Household energy purchase composition over time

	Years					
	2004			2011		
Energy mix	Number of observations	Mean	Std. Dev.	Number of observations	Mean	Std. Dev.
Biomass or mix with modern energy[a]	53	0.248	0.433	53	0.248	0.433
Mix of one or more with kerosene, electricity and battery-powered devices	150	0.701	0.459	70	0.327	0.470
Kerosene only	2	0.009	0.096	69	0.322	0.469
Electricity only	0	0.000	0.000	20	0.093	0.292
Battery-powered devices and others[b]	9	0.042	0.201	2	0.009	0.096

Notes: [a] Only two households purchased charcoal only, the remaining combined charcoal and/or fuelwood with one or more modern energy option. Only purchased biomass energy was considered here, biomass energy use from fuel collected by households was excluded
Though the number of households in this category didn't change over time, they were not the same households
[b] Others refers to household expenditures on candles and matches

2.5.3.1. Fuelwood scarcity and household food and energy expenditures

A FE-2SLS model was used to correct for endogeneity and selectivity by estimating per capita consumption energy and food expenditures based on Eq. (2.28) and the inverse Mills ratio predicted from Eq. (2.27) for household energy and food purchase decisions. The first-stage results for the instrumented wages for the total per capita energy expenditures are presented in Table 2.15. The results for each of the energy sources are not presented here, however, in all cases the instruments were found to have consistent and valid associations with the endogenous wage variables. The regression results indicate that increases in the mean per capita village income and the distance from villages to the nearest paved roads were associated with declines in fuelwood shadow wage, and both exhibited statistically significant and plausible relationships.

Table 2.15. First-stage wage equation results for the total per capita household energy expenditures from the FE-2SLS model, corrected for selectivity

Explanatory variables	Dependent variables (wages)		
	Fuelwood wage	Agricultural wage	Off-farm wage
Remittance (dummy)	–0.01 (0.04)	0.02(0.05)	–0.79*(0.47)
HH family size	0.01(0.01)	0.00(0.01)	0.12(0.10)
Age of HH head	–0.04***(0.00)	–0.01***(0.00)	0.01(0.02)
HH head education above elementary school	0.04(0.06)	0.58***(0.07)	0.56(0.68)
HH member education high school or above	0.09*(0.05)	0.40***(0.06)	0.42(0.56)
Highest HH member education level	0.00(0.01)	–0.08***(0.01)	–0.02(0.07)
ℓn HH land area	–0.03(0.03)	0.09***(0.03)	0.29(0.32)
ℓn number of HH trees	–0.02***(0.01)	–0.04***(0.01)	0.06(0.09)
ℓn number of HH livestock	0.15***(0.02)	0.14***(0.02)	–0.13(0.23)
Ratio of HH dependents to labourers	0.10***(0.02)	0.05*(0.03)	–0.31(0.25)
Female share of HH workforce	0.03(0.06)	0.05(0.06)	–0.60(0.61)
Year 2011 (dummy)	–1.48***(0.25)	–0.72(0.27)	3.59(2.62)
Inverse Mills ratio HH off-farm employment	–0.08(0.07)	–0.12*(0.08)	–0.24***(0.78)
Inverse Mills ratio HH fuelwood collection	–0.25***(0.02)	0.03**(0.03)	–0.35(0.26)
Distance of village to nearest paved road	–23.49***(2.70)	–3.07(2.97)	33.69(28.51)
ℓn mean per capita village income	–10.54***(1.42)	0.38(1.57)	16.32(15.01)
Agricultural cooperative (dummy)	–1.20(6.51)	4.28(7.16)	44.12(68.62)
Agr. coop. * ℓn mean village PCI	0.07(1.03)	–0.80(1.13)	–7.21(10.85)
ℓn mean village PCI * village distance to nearest paved road	3.39***(0.38)	0.41(0.42)	–4.52(4.04)
Agr. coop. * village distance to nearest paved road	0.25(0.16)	0.02(0.18)	–0.20(1.69)
Number of observations	428	428	428
F (20,194)	65.46	47.63	7.19
Uncensored R^2	0.87	0.83	0.43
F-test of excluded instruments	33.30	2.13	7.90
Angrist-Pischke F-test	43.95*** (0.00)	2.05** (0.05)	7.76*** (0.00)

Notes: * $P < 0 .1$, ** $P < 0.05$, *** $P < 0.01$

HH = household

The tests statistics for the validity of the instruments are reported at the bottom of the tables. The Angrist-Pischke statistics for each of the first-stage wage equations were statistically significant for all the per capita energy and food expenditures. Both the Cragg-Donald and Kleibergen-Paap rk LM statistics test results supported the rejection of weak and under identification in all of the per capita energy and food expenditures estimates. According to the Hansen-Sargan test results for the over-identification of instruments, the null hypothesis of zero correlation between the instruments and the error term cannot be rejected. The estimated coefficients of the inverse Mills ratios were statistically significant for kerosene and biomass in the respective per capita expenditure regression results, indicating that there was a selectivity problem.

The estimated coefficients of the final-stage per capita energy and food expenditures are reported in Table 2.16. The results reveal that increases in fuelwood scarcity have not resulted in increases in per capita expenditures on market purchased energy resources. Instead, higher shadow fuelwood collection labour wage was found to positively affect expenditures. The results indicate that per capita energy expenditures increased by about 0.73% when the shadow fuelwood collection labour wage increased by 1%. There are many plausible explanations for this relationship.

Fuelwood scarcity or increases in the opportunity cost of fuelwood production is normally expected to lead to increases in household per capita expenditures on purchased energy. This in turn is expected to reduce expenditures on food. There are two economically plausible explanations for this relationship: substitution and income effects. The energy substitution effect depends on various factors: valuation of shadow and market costs of energy, budget constraints, energy end use patterns, etc. Rural energy markets in Ethiopia, as in most developing countries, are highly imperfect. Substitution of purchased biomass for collected biomass depends on the comparison of the shadow opportunity cost with market prices. Nevertheless, bioenergy markets are typically poorly organized. Biomass trade is conducted only in semi-urban areas of the study villages. Local biomass scarcity is also associated with increased market prices for fuelwood and charcoal. The finding indicates that there is no empirical evidence that households increased per capita biomass expenditures in response to declines in the shadow wage of labour allocated to fuelwood collection. Traditional biomass energy use is only for cooking in rural Ethiopia, while modern energy options are typically used for household illumination.

Table 2.16. Final-stage FE-2SLS model results for per capita household energy and food expenditures, corrected for selectivity

Explanatory variables	Dependent variables (ℓn per capita expenditures)			
	Kerosene	Biomass	Total energy	Food
ℓn HH fuelwood wage	0.68(0.55)	0.59 (0.80)	0.73**(0.30)	3.17***(0.92)
ℓn HH agriculture wage	–4.25**(1.86)	–5.32**(2.68)	–2.150*(1.25)	2.01(3.09)
ℓn HH off-farm wage	0.04(0.12)	–0.30*(0.17)	–0.01(0.07)	–0.81***(0.19)
Remittance (dummy)	0.61*(0.37)	0.42(0.53)	0.26(0.21)	0.24(0.61)
HH family size	–0.07(0.09)	0.00(0.13)	–0.11**(0.05)	0.19(0.15)
Age of HH head	0.00(0.03)	–0.02(0.05)	0.02(0.02)	0.12**(0.06)
HH head education above elementary	3.14***(1.19)	3.87**(1.71)	1.85**(0.81)	–0.92(1.97)
HH member education high school or above	1.78**(0.87)	2.45**(1.25)	0.78(0.56)	–0.09(1.44)
Highest HH member education level	–0.27*(0.16)	–0.49**(0.23)	–0.15(0.10)	0.14(0.26)
ℓn HH land area	0.25(0.30)	0.46(0.43)	0.14(0.16)	0.06(0.50)
ℓn number of HH trees	–0.14(0.11)	–0.20(0.15)	–0.07(0.07)	0.12(0.18)
ℓn number of HH livestock	0.52(0.33)	0.73(0.47)	0.21(0.20)	–1.09**(0.55)
Ratio of HH dependents to labourers	–0.09(0.22)	0.48(0.31)	0.09(0.13)	–0.78**(0.36)
Female share of HH workforce	0.22(0.49)	0.25(0.70)	0.26(0.28)	–0.26(0.81)
Inverse Mills ratio HH biomass	0.94(1.79)	0.01(0.80)		–1.03(2.97)
Inverse Mills ratio HH kerosene	–3.47***(0.70)	1.54(2.57)		2.01*(1.17)
Inverse Mills ratio HH food	–0.51(0.80)	–1.07(1.15)		–0.31(1.33)
Year 2011 (dummy)	–0.86(0.56)	0.65(1.01)	–0.31(0.30)	–1.59*(0.93)
Number of observations	428	428	428	428
F (16,198)	3.59	1.86	1.50	2.37
Anderson canon. corr. LM statistic[a]	17.14***	17.14***	12.45*	17.14***
(p-value)	(0.01)	(0.01)	(0.05)	(0.01)
Cragg–Donald F–statistic[a]	2.08	2.08	1.50	2.08
Sargan statistics[b]	1.2	5.27	1.81	5.27
(p-value)	(0.95)	(0.38)	(0.88)	(0.38)

Notes: * P < 0 .1, ** P < 0.05, *** P < 0.01

[a] Under-identification and weak identification tests

[b] Over-identification test

HH = household

The estimated regression coefficient indicates that increases in fuelwood scarcity were associated with declines in per capita food expenditures. This indicates that an increase in fuelwood shadow wage (better access to forest biomass resources) resulted in an increase in labour time used for agriculture, with wage elasticity of +3.17. A 1% increase in fuelwood shadow wage was associated with a 3.17% increase in per capita food expenditures.

The estimated coefficient indicates that per capita kerosene expenditures were positively related to remittances (exogenous income). This indicates that households that received remittances spent more on kerosene relative to non-recipient households. This finding conforms to the results of a study on Mexican households, which found a positive association between remittances received from migrants in the United States and household gas expenditures (Manning and Edward, 2014).

Among household assets (land and livestock) the only significant effect, which was negative, was exhibited between livestock ownership and per capita food expenditures. This indicates that per capita food expenditures were inversely related to the number of livestock owned by households.

There was a positive and statistically significant relationship between household head education above the elementary level and all per capita energy expenditures. Furthermore, per capita kerosene expenditures were positively related to having a family member with high school or above education. This is consistent with theoretical expectations because higher education levels are expected to increase the opportunity cost of household energy collection. Moreover, education is also expected to increase awareness of the negative consequences of traditional biomass use and to facilitate transition to other forms of energy.

The estimated coefficient for household size and per capita energy expenditures was negative and statistically significant. This was expected because larger households have more labour available for biomass energy collection, resulting in less dependence on purchased energy. The greater the household size, the greater the need for other goods and services (education, health), thus there would be less money availability for energy purchases. 2011 dummy variable exhibited a negative relationship with per capita food expenditures, implying over that per capita food expenditures declined over time.

2.5.3.2.Fuelwood scarcity, energy purchase choice, and related determinants

The regression results for household energy mix choices are reported in Table 2.17. The discrete variable was created by categorizing households into five groups depending on the composition of purchased energy sources as shown in Table 2.14. The estimated coefficient for fuelwood collection labour shadow wage indicates that the likelihood of choosing kerosene relative to biomass declined with increases in fuelwood scarcity. This indicates that greater fuelwood scarcity makes households more likely to purchase biomass than kerosene. This implies that fuelwood scarcity might inhibit fuel transition as the likelihood of households purchasing biomass (charcoal and fuelwood) increases relative to purchasing kerosene or other energy alternatives.

The estimated coefficients for agriculture and off-farm wages indicate that with improvements in living standards or wage income, households are more likely to choose electricity only or kerosene increases relative to biomass. Interestingly, this may reflect the role of livelihood improvements in determining household energy decisions. The higher the wage income, the more likely a household chose to purchase electricity only or kerosene relative to biomass. Higher agricultural or off-farm wages imply greater disposable income. Furthermore, agricultural production is likely associated with greater potential to generate alternative biomass fuels such as cattle dung and crop residues; thus, lowering demand for market biomass resources.

Table 2.17. Multinomial logit model results of purchased energy mix among Ethiopian sample households

Explanatory variables	Dependent variable (discrete energy choice)			
	Electricity only	Kerosene only	Battery powered and others only	Mix of modern energy options[a]
ℓn HH fuelwood wage	0.28 (0.41)	2.25***(0.60)	–2.04**(0.80)	0.06(1.00)
ℓn HH agricultural wage	3.54*(2.06)	1.40(2.16)	–16.31*(9.89)	–8.77(6.71)
ℓn Off-farm wage	0.34***(0.11)	0.76***(0.14)	–1.58**(0.68)	–0.55(0.34)
Remittance (dummy)	–0.41(0.36)	0.47(0.56)	–2.25*(1.24)	0.48(0.79)
HH family size	–0.13*(0.07)	–0.20*(0.11)	0.45*(0.24)	0.12(0.13)
Age of HH head	0.05**(0.02)	0.12***(0.03)	–0.27**(0.11)	–0.08(0.06)
Remittance (dummy)	–2.75**(1.38)	–1.54(1.50)	9.09(6.18)	6.42(4.65)
HH family size	–1.38(0.95)	–0.25(1.12)	6.86*(4.02)	–13.14***(2.71)
Age of HH head	0.18(0.17)	0.00(0.19)	–1.30(0.81)	–0.71(0.54)
HH head education above elementary	–0.28(0.27)	0.38(0.40)	1.85(1.17)	0.09(0.68)
HH member education high school or above	0.18*(0.10)	0.12(0.13)	–0.25(0.32)	–0.14(0.26)
Highest HH member education level	–0.46*(0.26)	–0.71**(0.32)	2.50*(1.42)	1.01(0.91)
ℓn HH land area	–0.33(0.20)	–0.15(0.32)	0.10(0.75)	–0.17(0.52)
ℓn number of HH trees	0.07(0.63)	0.05(0.94)	–0.43(1.29)	–0.44(0.92)
Year 2011 (dummy)	–0.12(0.53)	2.92***(0.89)	15.29***(0.95)	–3.52**(1.79)
Constant	–19.13*(10.51)	–20.60*(10.85)	79.86(53.08)	47.26(34.82)
Number of observations	20	71	11	220
Pseudo R^2		0.29		
Wald chi^2 (104)		3435.45(0.00)		
Log pseudo-likelihood		–371.10		

Notes: * $P < 0 .1$, ** $P < 0.05$, *** $P < 0.01$
Biomass energy was the reference group
[a] Mix of two or more energy sources including electricity, kerosene, battery powered devices, and others
Robust standard errors shown in parentheses
HH = household

The positive coefficient value indicates that the greater the household size, the more likely it is to purchase electricity or kerosene elative to biomass energy resources only. This finding conforms to the results for per capita energy expenditures, which is likely due to labour availability for biomass collection and increases in demand for non-energy goods and services as explained above. In the literature the effect of household size on household energy demand is indeterminate.

The estimated coefficient indicates that increases in the number of trees on private property were associated with increased likelihood of household choice of electricity relative to the purchase of biomass energy resources. Increased number of trees implies greater availability of biomass or lower opportunity costs of collecting it. Trees may also offer households income generating opportunities and thereby increase disposable income.

The estimated coefficient for the year 2011 was negative with respect to kerosene only, and battery powered devices and other energy options only. This implies that over the study period households choose to purchase more of those energy sources relative to biomass energy resources. In contrast, over the study period households exhibited less consumption of a mix of modern energy options relative to biomass energy.

2.5.3.3.Discussion of the welfare implications

There appears to have been little empirical research conducted that has examined the fuel-food trade-offs with respect to the linkages between fuelwood scarcity (costs of household collected fuelwood) and per capita energy and food expenditures or budget allocation decisions. Moreover the interaction of supply side factors or fuelwood scarcity on the mix of energy options purchased by households does not appear to have been adequately researched. However, there is a clear value in considering this aspect to improve understanding of energy transition at the household level.

An important policy implication from the results of this research concerns the key role of afforestation or reforestation programmes on household welfare in terms of per capita energy and food expenditures and energy purchase decisions. The econometric mode revealed that increases in access to biomass resources or forest contributed positively to per capita energy and food expenditures. To the contrary, increases in fuelwood scarcity had a negative relationship with per capita energy and food expenditures, which may adversely affect food and energy security. Consequently, in the discrete choice MNL model greater access to forest or greater fuelwood collection labour wage were found to be positively related with the likelihood of households purchasing kerosene only compared to biomass energy resources.

The research findings lend support for the importance of policies that support off-farm employment and increase household productivity. However, in the case of per capita energy and food expenditures, this may seem counterintuitive in two situations. The negative effect of agriculture wage on per capita energy expenditures seems implausible. Increases in agricultural wage are expected to lead to increases in disposable income or energy purchases. Nevertheless, more productive households might have generated more biomass energy from farming activities (that produce cattle dung and crop residues used as fuels) and thus spend less per capita on energy. On the other hand, the negative effect of off-farm wage on per capita food expenditures also seems implausible. From a theoretical perspective this would be expected to have a positive effect on food expenditures. In rural Ethiopia, however, off-farm wages are typically low; such work is mostly performed for other farmers for meagre wages that may not represent meaningful income or the ability to increase per capita food expenditures. More typical remunerated employment opportunities are highly limited. On the other hand, increases in off-farm wages might contribute to enhanced household food production.

Greater agricultural and off-farm wages resulted in a greater likelihood that households would purchase kerosene or electricity only relative to biomass energy. In particular, the statistically significant and positive coefficient of off-farm wage relative to the choice of electricity and kerosene purchases conforms to the findings of previous studies. One study found that for Ugandan households there was a direct relationship between electricity consumption and income (Lee, 2013). In the case of Nepalese households, evidence was found that supports the ‘environmental Kuznet’s curve’ concept, however, this was only exhibited at the top end of the wealth distribution with respect to greater off-farm business assets (Baland et al., 2010). An empirical study from Nepal found that increased exposure to extra-household employment (i.e. in community organizations) stimulated fuel substitution (Macht et al., 2007). The role of policies such as micro-credit programmes that support self-employment initiatives, private businesses, and off-farm employment need greater attention and should be paralleled with sustainable energy provisions.

Education was found to be highly associated with household energy substitution. The opportunity cost of fuelwood collection is expected to increase with education. The positive effect of education variables on per capita energy expenditures conforms to earlier empirical findings. A study on Guatemalan households indicated that education made the substitution of modern energy options for traditional sources more attractive through increasing the opportunity cost of fuelwood collection (Heltberg, 2005). Similarly, another study found that when the opportunity cost of fuelwood collection rose, fuelwood collection became economically unprofitable among better educated Nepalese households (Adhikari et al., 2004).

In general, the research findings conform to the energy stacking or multiple fuel use concept. Households consumed variable compositions of biomass, kerosene, battery powered devices, and other energy options. More importantly, aside from income, other wealth indicators, and socio-economic factors the opportunity cost of fuelwood collection and relative labour earnings from different sources were significant determinants of household fuel-stacking behaviour. The findings of also support earlier research that underlined the role of education and various policy tools that help households ‘leapfrog’ up the ‘energy ladder’ from traditional to modern energy sources (Heltberg, 2004; Lee, 2013).

The lack of information on the amount of household collected bio-based energy for domestic consumption in the base survey hindered the ability to compute shadow prices from shadow wages. The results of cross-sectional data analyses on the effects of fuelwood scarcity and other socio-economic variables on household biomass energy use and substitution are provided below.

2.5.4. Household bio-based energy utilization and welfare effects of fuelwood scarcity

A better understanding of household energy use and substitution is necessary for examining the linkages between fuel-food trade-offs and rural livelihoods, and for investigating policy solutions for the rural energy crisis in Ethiopia. Sample households consumed multiple fuels that are either complementary or substitutes. The extent of substitution between energy sources depends on cultural preferences, lifestyle, and the intended purpose of the energy used. Different biomass energy resources commonly used in Ethiopia may be used to substitute for one another. Low-quality agricultural fuels are typically used as a backup for fuelwood for residential cooking or heating needs.

Table 2.18. Descriptive statistics of the variables used in the household energy consumption model

	Statistical measure			
Variables	Mean	Std. dev.	Min	Max
Dried cattle dung consumed (kg/year)	71.77	106.06	0.00	600.00
Crop residues consumed (kg/year)	14.01	37.25	0.00	250.00
Fuelwood consumed (kg/year)	1959.85	1156.17	0.00	5557.50
Charcoal consumed (kg/year)	111.32	320.53	0.00	1944.00
Total biomass consumed (kg/year)	2,156.95	1,217.96	0.00	5,814.00
ℓn shadow fuelwood price (ETB/kg)	–1.44	1.65	–5.14	1.50
ℓn kerosene price (ETB/Litre)	2.89	0.10	1.59	2.94
ℓn shadow cattle dung price (ETB/kg)	2.49	2.50	–0.83	8.30
ℓn charcoal price (ETB/kg)	–0.02	0.26	–1.50	0.81
Female share of HH labour force	0.50	0.25	0.00	1.00
HH head literacy (dummy: 1 if head attended formal school, 0 if otherwise)	0.73	0.44	0.00	1.00
HH gender (dummy: 1 if male, 0 if otherwise)	0.44	0.50	0.00	1.00
Improved efficiency biomass stove (dummy: 1 if owned, 0 if otherwise)	0.10	0.30	0.00	1.00
[a]ℓn HH non-labour income (in 100's ETB/year)	1.71	3.79	0.00	12.60
ℓn population density (#/km^2)	5.52	0.81	4.61	6.55
[a]ℓn HH electricity expenditures (in 100's ETB/year)	0.59	0.91	–0.65	4.62

Note: HH = household

The shadow prices of fuelwood and agricultural fuels were calculated using the interaction of the shadow wages (ETB/hour) of fuel and agricultural activities based on Eq. (2.17). This has two important implications: (i) the extent to which forest degradation or deforestation affect the amount of fuelwood consumed, and (ii) to capture the quality of labour engaged in fuel collection. The descriptive statistics of additional variables used in the energy consumption analysis are given in Table 2.18. The remaining variables are presented in Table 2.6. In 2011 about 10% of the sample households had adopted improved efficiency biomass stoves. Fuelwood constituted about 95% of household total biomass energy use, followed by cattle dung (3.5%), crop residues (0.7%), and charcoal (0.3%).

Fuelwood is the predominant source of energy in the study sites; about 94% of the sample households reported using it. Only two of the households reported using only agricultural fuels. Empirical evidence suggests that fuelwood scarcity leads to shifts towards inferior agricultural fuels, primarily due to the greater smokiness of cattle dung and the lower energy content of crop residues (see Agarwal, 2010; p. 327). Some studies have found that fuelwood and cattle dung used by households are energy complements rather than substitutes for cooking (Mekonnen, 1999; Mekonnen and Köhlin, 2008; Damte et al., 2012).

The results of the analysis of fuelwood, charcoal, and agricultural fuel consumption among households are presented in Table 2.19. Cross-price elasticity was used to examine for substitution effects. Total biomass energy and fuelwood consumption functions were estimated using the ordinary least square (OLS) approach in the final stage equation by using predicted shadow prices because there were no selectivity or censoring problems identified.

Table 2.19. Household biomass energy use determinants

	Dependent variables (amount of energy in kg/year)			
	Charcoal[a]	Agricultural fuels[a]	ℓn fuelwood[b]	ℓn total biomass[b]
Explanatory Variables	Marginal effect	Marginal effect	Coef.	Coef.
	–0.331	–3.484	–0.377***	–0.299***
ℓn shadow fuelwood price	(19.293)	(4.323)	(0.050)	(0.039)
	–257.872***	6.183	0.059	–0.449**
ℓn market kerosene price	(84.392)	(48.385)	(0.277)	(0.198)
	0.305*	–0.080	–5.37E–05	1.00E–04
ℓn shadow cattle dung price	(0.175)	(0.051)	(3.70E–04)	(4.87E–04
	–106.513**	–6.952	–0.034	–0.145
ℓn charcoal price	(42.783)	(13.975)	(0.114)	(0.099)
ℓn shadow fuelwood wages*	–29.858**	–4.005	0.066***	0.032*
ℓn number of HH livestock	(12.579)	(2.524)	(0.022)	(0.018)
ℓn shadow fuelwood wages*	–8.567	5.380	0.091***	0.079***
ℓn HH land area	(15.367)	(3.933)	(0.026)	(0.023)
	59.909***	–1.492	–0.009	0.027
ℓn number of HH livestock	(18.377)	(4.475)	(0.039)	(0.032)
	–25.291	–9.033	–0.029	–0.065
ℓn HH land area	(29.167)	(9.684)	(0.053)	(0.053)
	45.760***	12.131***	0.600***	0.499***
ℓn fuelwood time	(16764)	(3.195)	(0.054)	(0.046)
	45.037	–23.350***	0.040	0.075
HH head literacy (dummy)	(39.381)	(8.907)	(0.054)	(0.055)
	–9.591	3.857	–0.113**	–0.084*
HH family size	(27.485)	(9.868)	(0.050)	(0.047)
	–111.533*	–0.333	0.011***	0.009**
HH family size^2	(59.101)	(0.904)	(0.004)	(0.004)
	–76.124*	–0.439	0.004	0.004*
Age of HH head (years)	(43.606)	(0.317)	(0.002)	(0.002)
	9.783*	8.961	–0.109	–0.095
HH head gender	(5.593)	(9.314)	(0.067)	(0.065)
Female share of HH labour	0.128	–9.705	0.072	–0.032
force	(2.410)	(17.063)	(0.126)	(0.098)
HH member education high	1.529	11.765	–0.080	–0.041
school or above	(1.075)	(14.283)	(0.078)	(0.075)
Highest HH member	–31.365	–0.444	–0.005	–0.004
education (years)	(37.273)	(1.529)	(0.011)	(0.010)
Improved efficiency biomass	13.687	–9.666	–0.094	–0.067
stove use	(60.455)	(14.091)	(0.093)	(0.083)
	5.063	0.464	0.014**	0.015**
ℓn non-labour income	(4.208)	(0.981)	(0.007)	(0.007)
	6.382	–63.673***	–0.375***	–0.341***
ℓn population density	(39.645)	(12.602)	(0.101)	(0.093)
	–9.814	–2.939	–0.074*	–0.085**
ℓn electricity expenditures	(18.701)	(6.466)	(0.040)	(0.038)
			5.023***	7.180***
Constant			(0.950)	(0.720)
Uncensored observations	31	154	201	203

R^2			55	67
Pseudo R^2	0.105	0.05		
Explanatory variables	Charcoal[a] Marginal effect	Agricultural fuels[a] Marginal effect	ℓn fuelwood[b] Coef.	ℓn total biomass[b] Coef.
F-statistic	4.92	4.19	12.13	11.37
Pseudo-likelihood	–289.511	–975.94		

Notes: * $P < 0 .1$, ** $P < 0.05$, *** $P < 0.01$

[a] Dependent variables are the amounts in kg/year

[b] Dependent variables are in logarithm values of the amounts in kg/year

Standard errors are presented in parentheses

HH = household

The Tobit model was used to estimate charcoal and agricultural fuel consumption due to the presence of censoring. In the energy consumption equations, both OLS and Tobit estimates were corrected for heteroscedasticity using the heteroscedasticity consistent covariance estimator of White (1980).

The research question regarding determinants of bio-based energy consumption was addressed by examining household energy use behaviour, wage and price effects, and energy substitution elasticity. Substitution of agricultural fuels for fuelwood represents an important fuel-food trade-off. The elasticity of fuelwood consumption with respect to its own shadow price was negative. This finding is consistent with theory and conforms to previous empirical research findings. Higher shadow price reflects forest or fuelwood scarcity that manifests as greater labour costs required to collect fuelwood. This suggests that households reduced fuelwood use in response to increased labour costs and energy prices.

Previous studies found a similar influence of increased shadow wage on household fuelwood use among rural Ethiopian households (Mekonnen and Köhlin, 2008; Damte et al., 2012). It is well established that an increase in the opportunity costs of fuelwood reduces fuelwood use (Heltberg, 2000; 2005: Wang et al., 2012). Among both urban and rural households in Guatemala there was a negative own-price effect of fuelwood (Heltberg, 2005). Another study of rural Ethiopian household energy behaviour found that increases in labour required for fuelwood collection resulted in a lower likelihood of households using traditional biomass as their main fuel compared to modern energy alternatives (Guta, 2012a).

The price elasticity values of fuelwood and total biomass consumption with respect to fuelwood shadow price were about –0.38 and –0.30 respectively and both were significant at a 1% significance level (Table 2.16). Fuelwood scarcity reflected in the opportunity cost of time used for fuelwood collection or shadow price is an important driver of household energy use, with policy implications for afforestation and sustainable forest use. Increased access to forests reduces household travel cost. Hence greater access to forest is expected to reduce the cost of fuelwood collection, which is expected to enhance household welfare. A decrease in the quality or quantity of forest resources is accompanied by increased fuelwood collection effort. Households adjusted to forest scarcity by reducing the amount of fuelwood consumed as reflected in shadow price. This result is consistent with the finding of Pattanyak et al. (2004) that greater access to forest enhances household welfare by reducing travel costs. Among Malawian households it was found that rural women benefitted from increased biomass availability in the community (Bandyopadhyay et al., 2011). That study, however, did not explicitly model how scarcity influences household bio-based energy consumption through shadow prices apart from an analysis of the labour use effect of the physical availability of biomass at the community level. At the 1% significance level, fuelwood and total bio-based energy consumption were positively associated with annual time spent on fuelwood collection.

The shadow cost or price of fuelwood collection reflects fuelwood scarcity. It is used to examine the effect of forest scarcity on household energy utilization in a manner that that reflects the opportunity cost of time. This in turn depends on household access to forest resources. In China the distance to forests was found to be negatively correlated to fuelwood collection and positively correlated with coal use in villages with better market access, but in remote villages the distance to forest did not affect the quantity of fuelwood collected (Chen et al., 2006). Previous studies of Ethiopian households found that the choice of biomass energy relative to modern energy was negatively correlated with the amount of time spent on fuelwood collection (Guta, 2012a).

Scarcity of cattle dung implies greater labour required to collect it from communal grazing areas. The shadow price of agricultural fuel was not statistically significant. This is likely because agricultural fuels are by-products of agricultural production and therefore the two are complementary. However, the use of agricultural waste for energy presents an opportunity cost for food production.

A good is considered as a substitute for another if price increases for one good result in increased consumption of the other. The existence of substitution is measured in terms of price responses between the two fuels (Table 2.17). The use of agricultural fuels for household energy creates opportunity costs in terms of food security due to the foregone opportunity of using them for soil fertility management to improve productivity (Heltberg, 2000; Mekonnen and Köhlin, 2008). The cross-price elasticity values of fuelwood and agricultural fuel were indeterminate, indicating evidence of substitution. These results are consistent with studies in Namibia and Ethiopia that found no evidence of fuel substitution between fuelwood and lower quality agricultural fuels (Mekonnen, 1999; Mekonnen and Köhlin, 2008; Palmer and Macgrego, 2009; Damte et al., 2012). Use of agricultural biomass for energy has serious implications for the water-energy-food nexus (Rasul, 2014).

Kerosene market prices from the study sites were incorporated into the analyses. The cross-price elasticity of household biomass energy use with respect to kerosene price was not significant in the cases of fuelwood and agricultural fuel consumption, but was negative and significant with respect to charcoal and total biomass consumption. This implies that kerosene is not a substitute for biomass energy, which is consistent with expectations as kerosene is typically used for illumination as opposed to cooking.

Electricity consumption expenditures were incorporated into the econometric model. Like fuelwood, charcoal is chiefly used for cooking. Household charcoal demand was met by market sources. Most households in semi-urban areas purchased both charcoal and electricity.

Approximately 38% of the sample households had access to electricity in 2011. Model results indicate that fuelwood use was negatively associated with household electricity expenditures. *Ceteris paribus*, a 1% rise in electricity expenditures resulted in fuelwood and total biomass consumption declines of 0.074% and 0.085% respectively. The parameters are proxy values for the elasticity of the effect of electricity on household bio-based energy use. This negative relationship has two likely explanations. First, areas with electricity are more likely to have greater off-farm employment opportunities, which negatively affect fuelwood collection through a labour substitution effect. Second, electricity can be a substitute for fuelwood.

To answer the research question about how to improve the efficiency of biomass energy use, the impacts of the use of improved efficiency biomass stoves on household biomass energy use were examined. However the result suggests there is limited empirical support that household use of improved efficiency biomass stoves reduces biomass energy consumption. Although this seems counter intuitive, the result may be attributable to the limited use of improved efficiency biomass stoves among the sample households (only 22 households or 10%). Ethiopia is promoting broader adoption of these stoves with the goal of achieving health, environmental, and social benefits such as reducing the exposure of women and children to IAP.

Table 2.20. Price, income and expenditure elasticity of household energy consumption in Ethiopia

Price, income, and expenditures	Energy types			
	Charcoal[a]	Agricultural fuels[a]	Fuelwood	Total biomass
Fuelwood price	–0.003	–0.041	**–0.377**	**–0.299**
Market price of kerosene	**–2.316**	0.073	0.059	**–0.449**
Agricultural fuel price	**0.003**	–0.001	–5.37E–05	1.00E–04
Charcoal price	**–0.957**	–0.082	–0.034	–0.145
Non-labour income	0.045	0.005	**0.014**	**0.015**
Electricity expenditures	–0.088	–0.035	**–0.074**	**–0.085**

Notes: Only highlighted elasticity values were significant (see Table 2.16)

[a] Charcoal and agricultural fuel elasticity were computed by dividing the parameter from Table 2.16 by the mean of the amount of the respective energy consumed by households given in Table 2.15

There is contrasting evidence regarding the impact of improved efficiency biomass stoves on household fuelwood consumption. An empirical study from a poor, forest-rich region of southeast China found that improved efficiency stove ownership was associated with increased fuelwood collection (Chen et al., 2006). A study of Pakistani households found that improved efficiency cook stove use was effective at reducing fuelwood consumption in areas where fuel was scarce (Mobarak et al., 2012). A study from Nepal also suggested that programmes should target areas where fuelwood scarcity is high and where people already perceive the negative impacts of deforestation on fuelwood availability (Amacher et al., 1993). There is other evidence that more efficient stove use is less successful in areas where people collect fuelwood or do not perceive deforestation as a problem (Barnes et al., 1994). To date there is no published research findings on the impacts of improved efficiency biomass stoves on household biomass energy use in rural Ethiopia. Mekonnen and Köhlin (2008) found that household use of traditional three stone stoves was associated with high levels of woody biomass use. There is also uncertainty about the impact of efficiency improvement on household fuel consumption due to the ‘rebound effect' or the tendency of positive gains to be offset over time. This is often due to increased convenience and income, and may also be due to household preferences for fuelwood. Households in Sudan exhibited a 'rebound effect' associated with improved stove use and charcoal consumption (Zein-Elabdin, 1997).

Greater use of improved efficiency biomass stoves can be a key policy objective for addressing not only health, social, and environmental problems; but also for improving energy efficiency at the household level. The results suggest that increasing electricity access, broader improved efficiency stove dissemination, and rural electrification initiatives have promising potential for improving energy security in Ethiopia. A recent study that combined 13 technical, economic, environmental, and social sustainability indicators to evaluate rural energy sustainability in six countries (China, India, South Africa, Sri Lanka, Bangladesh, and Ghana) from 1990 to 2010 suggested that rural energy sustainability has improved over time in all of the countries except Ghana (Mainali et al., 2014). That study also found that improvements were mainly achieved from increasing rural electricity use and access to cleaner and more efficient cooking fuels.

Economic wealth is considered an important determinant of household energy consumption, however, evidence of this relationship is mixed. One study found that fuelwood consumption declined with increased wealth in rural China (Démurger and Founier, 2011). Per capita income increases were also found to reduce per capita fuelwood consumption in rural China (Jingchao and Kotani, 2012). Other studies have found that fuelwood is a normal good among poorer households, but that it becomes an inferior good when income rises (Arnold et al., 2006; Shi et al., 2009). Increased household income was found to be an important determinant of fuelwood substitution in rural China (Wang et al., 2012).

The interaction of shadow wage with assets (land and livestock) had a significant positive effect on both fuelwood and total biomass energy use among the sample households. Land assets had a negative association with household charcoal consumption and statistically significant. This may be due to the greater ability of households with more land and livestock to plant trees and produce dried cattle dung. A study on Indian households also found complementarity between fuelwood collection and cattle grazing (Dayal, 2006), which would be expected to reduce the opportunity cost of collection and contribute to increased use of fuelwood.

Household fuelwood use had positive non-labour income elasticity values and statistically significant. The model indicated that a 1% increase in non-labour income was associated with fuelwood use increases of 0.014%, hence fuelwood appears to be a normal good among Ethiopian households. Since fuelwood is the dominant bio-based fuel in Ethiopia, total biomass consumption was also positively associated with non-labour income, with an elasticity value of 0.015%. This result is consistent with previous studies that found positive income elasticity for woody biomass in rural Ethiopia (Mekonnen, 1999; Mekonnen and Köhlin, 2008).

Improvement in household welfare is often associated with increasing preference for more refined fuels. Growing urban demand for charcoal in combination with unsustainable production practices can cause local environmental problems, particularly in Africa (Arnold et al., 2006). The price elasticity of charcoal was nearly unitary. A 1% increase in the price of charcoal was associated with a 0.96% decline in charcoal consumption. The positive cross-price elasticity of charcoal use with respect to agricultural fuel likely suggests that households located in peri-urban areas prefer to purchase charcoal when the shadow price of agricultural fuel increases, although the elasticity value was very low (0.003). Positive elasticity or substitution may arise from the fact that those households in peri-urban areas have limited access to agricultural fuels and therefore must purchase charcoal to complement fuelwood as opposed to their rural counterparts. Peri-urban households also typically have better access to markets and modern energy options and hence agricultural fuels are likely considered inferior. In general, biomass energy has also been found to be inferior among rural households in Ethiopia (Guta, 2012a). Similar findings have been reported among Nepalese households (Baland et al., 2010). An empirical study from Uganda found that household energy mix conformed to the energy ladder concept (Lee, 2013). That study identified public infrastructure, income, and education as the major drivers of household fuel substitution of solid biomass with modern energy options.

Fuelwood and total biomass energy consumption had significant positive non-linear associations with household size, but their linear relationship was negative and not statistically significant. Positive relationships between household size and fuelwood use have also been observed by other studies in Ethiopia, Guatemala, and Burkina Faso (Heltberg, 2005; Ouedraogo, 2006; Mekonnen and Köhlin, 2008). The effect of family size was indeterminate. Cooking for larger families may result in economies of scale, implying less per capita energy requirements, however, family size is also directly related to labour availability for biomass collection. One empirical study from China found that larger households exhibit lower per capita energy use (Jingchao and Kotani, 2012). A concave relationship between household size and biomass use was observed by another study of Chinese households (Démurger and Founier, 2011). The negative and significant association of household charcoal consumption with family size in non-linear is theoretically consistent. Family size is expected to be directly related to expenditures and therefore larger households may have less per capita disposable income for charcoal purchases.

Household energy choice may be affected by the gender of the household head. Household heads have considerable influence on household decisions in rural Ethiopia, particularly about energy use. The relationship between charcoal consumption and male-headed households was positive and statistically significant, which is theoretically consistent because males are likely to prefer to buy charcoal than collect biomass. However, there is limited empirical evidnce of the positive association of household fuelwood consumption with the adult female share of the household workforce. In Malawi one study found that women spend greater time on fuelwood collection in areas where biomass is scarce (Bandyopadhyay et al., 2011).

Another important determinant of household energy use is education. Biomass energy use was negatively associated with household education indicators. A household head with formal education was associated with a 5% decline in agricultural fuel consumption. Household head literacy was associated with reduced agricultural fuel consumption of about 23.4 kg per year relative to illiterate counterparts. An increase in the number of school years attended by the most highly educated family member was negatively associated with fuelwood consumption. These associations may reflect a preference for alternative fuels or greater off-farm income for the purchase of alternative energy sources among more educated households.

Population density also has important implications for rural household energy use behaviour. Higher population density implies greater pressure on local forest resources due to a higher proportion of land converted for agriculture and greater forest exploitation. Thus population density is expected to help account for the spatial variability of biophysical resource availability such as land, forests, and water. High population density in rural areas of Ethiopia has resulted in the drastic loss and degradation of communal forests, lands, and other resource constraints, with significant implications on household energy consumption. Agricultural fuel consumption, fuelwood consumption, and total biomass consumption all had negative associations with population density as expected that were statistically significant at 1%.

2.6. Conclusion and recommendations

This chapter is devoted to the investigation of household bio-based energy utilization behaviour in order to better understand the trade-offs between food security and welfare effects. These linkages between fuel and food production were empirically investigated to reveal welfare implications of changes in the shadow wages of labour on household labour allocation, both separately for each activity and jointly with the implementation of a panel data analysis approach. The effects of fuelwood scarcity were examined by investigating the relationships among wages and labour allocation to activities. The findings indicate that labour allocated to fuelwood collection was associated negatively with agricultural wage, but that agricultural labour was positively related to fuelwood wage, both of which were consistent with the original research hypotheses. Fuel collection and agricultural activities had negative cross-wage substitution elasticity as expected. Thus, the empirical evidence supports the hypothesis that fuel-food trade-offs exist from a labour resource perspective. There are numerous explanations for the degree of substitutability. The conditions included whether each fuel type was an inferior or normal good, whether households were net fuel sellers or buyers, and the demand for food and fuel relative to leisure as income increases. The negative cross-wage elasticity of the substitution of fuel collection with respect to off-farm employment activities conforms to the findings of other empirical studies from developing countries.

The sample households depended on diverse energy sources to meet their residential energy demand. Modern energy options such as electricity, kerosene, battery powered devices, and others can only be purchased. However, households can collect and sometimes purchase biomass energy resources, which means that the opportunity cost of household collection of biomass affects energy and food purchase decisions. Fuelwood scarcity or deforestation was found to be associated negatively with household welfare in terms of per capita energy and food expenditures. Moreover, this finding suggests that fuelwood scarcity or declines in fuelwood collection labour shadow wage resulted in a lower likelihood of households purchasing modern energy options relative to biomass energy resources. This implies that increases in biomass availability improve household welfare, being associated with increased per capita food and energy expenditures, and a greater likelihood that households would purchase modern energy options, both of which enhance energy and food security.

Cross-sectional econometrics were applied to examine household bio-based energy utilization. The model results are consistent with the findings of previous studies and also offer relevant policy insight. There was no substitutability observed between the use of fuelwood and agricultural fuels, but rather complementarity, as the latter are often used as a backup to the former. Fuelwood scarcity was reflected in increasing shadow prices or opportunity costs that resulted in reduced fuelwood use by sample households. Fuelwood was a normal good with non-labour income elasticity values. The limited but statistically significant elasticity of fuelwood and overall biomass consumption with respect to electricity expenditures imply that energy substitution of traditional biomass resources with more refined alternatives is very sluggish. Substitution is constrained by the lack of access and income, which have important policy implications.

Policy tools that influence the price of biomass energy substitutes such as subsidies for biogas systems or briquettes may be more effective means of hastening the transition from traditional biomass energy use towards modern alternatives. Investments in sustainable energy use, including both grid and off-grid electricity from cleaner sources such as solar, micro-hydroelectric, and other alternative resources deserve concerted attention. In addition to addressing rural energy problems greater biogas development also has the potential to contribute to agricultural development. The results also provide support for efforts to increase the supply of fuelwood through afforestation policy and improving the sustainability of forest resource use.

Chapter Three

Energy sector model for assessing Ethiopia's future energy security, uncertainties, and renewable energy resource options

3.1. Introduction

Globally, the issue of energy security has gained increasing attention. Energy security implies sustainable supply; acceptable sources, cost, price stability, and continued or improved accessibility; and avoiding threats to public safety or health and the environment. There are a number of underlying impetuses for increased energy security awareness. The vulnerability of nationwide energy systems to various supply and demand risks is a pressing challenge. In many developing countries the lack of access to modern energy technologies is also a major predicament.

There are few studies that include energy sector models for Sub-Saharan African countries. Jun et al. (2009) developed mechanisms for measuring the cost of energy security in terms of supply disruption and price volatility, and considered the degree of energy supply and demand concentration using the Hirschman-Herfindahl index. The authors considered balanced fuel supply and demand, relative price stability, and abundance as indicators of energy security. A number of other studies have conceived of energy security in terms of supply security (Correlje and Linde, 2006; Mane-Estrada, 2006; Turton and Barreto, 2006). Two recent papers have discussed the concept of energy security in Pacific Asia (Vivoda, 2010; Sovacool, 2011). Sovacool (2011) described the energy security conundrum as "how to equitably provide available, affordable, reliable, efficient, and environmentally friendly energy services," which is both a technological and policy challenge. Another paper reviewed comprehensive energy security challenges in Pacific Asia and proposed eleven energy security dimensions and a number of attributes of each dimension (Vivoda, 2010).

The concept of energy security has rarely been dealt with for Africa, although both narrow and broad definitions of energy security have been described for this region. "The former refers to simply maintaining sustainable energy supplies to meet demand. The broader definition includes the security of energy supply infrastructure from "international criminal threat as well as safeguarding against inadvertent failures of normal operations due to malfunction, damage, and breakdown of energy supply infrastructure, and the resulting effects on national socio–economic and environmental well–being. Energy security is often used to refer to the pervasive nature of energy in the sense that energy is a vital input in almost every activity and therefore any interruption in delivery has negative impacts across society" (EEA, 2009).

Ethiopia has faced a myriad of energy problems. In addition to a general lack of power transmission infrastructure, major challenges have arisen from deforestation, forest and land degradation, and problems associated with public health, productivity, and gender inequity. The escalating prices of petroleum products add to existing pressures on the country's energy sector and have strained the national economy due to the country's complete reliance on oil imports.

Over 90% of Ethiopia's electricity generation in 2010 was hydroelectric power, which is vulnerable to frequent and persistent drought that is characteristic of the region (EEPCO, 2011). The World Energy Trilemma report (2013) identified the challenges of Ethiopian energy security, equity and environmental sustainability and indicated that "the country continues to struggle with high transmission and distribution losses and homogenous electricity mix because it is almost solely reliant on hydropower." The lack of efficient biomass energy technology is also a critical problem, not only because of the squandering of biomass resources as implied in the previous chapter, but also the adverse health effects of IAP exposure that disproportionately affects women and children. Global energy challenges need to consider public health threats comprehensively, both indoor as well as outdoor.

In agriculture–based economies like Ethiopia's, modern biomass energy technology can be the key to energy security. Investment in renewable energy, technological innovation, and improving biomass use efficiency are expected to improve energy security. Modern biomass energy generation technology is unique in that it may be appropriate for most end uses and for the production of all sorts of energy. Developing biomass energy value chains can generate opportunities for sustainable development, including: job creation, clean energy generation, and rural livelihood diversification. There are critical crosscutting issues that need to be addressed, however, including the competing uses of biomass resources such as for food, fodder, fuel, etc. These issues make it imperative to empirically explore technological innovation and resource-use efficiency in order to evaluate strategies for maximizing benefits and reducing risks. The lack of in-depth research on this issue in Ethiopia is what motivated this component of the study.

There is scant quantitative evidence of the various uncertainties involved in determining the country's future energy security. A long-term, least-cost energy investment model was developed for this study to investigate the contribution of technological and efficiency innovation to energy security in Ethiopia by evaluating distinct potential energy development pathway scenarios. The main research hypothesis of this effort is that more sustainable use of renewable energy resources and relevant technological and efficiency innovations or improvements in the cost-competitiveness of renewable energy through learning and direct experience will contribute to energy security as these factors are expected to contribute to the substitution of alternative technologies for hydroelectric energy. It is vital that policy makers make optimal decisions regarding least-cost energy investment options for integrated energy source diversification. We posed the following research questions. What is the least-cost energy diversification option for Ethiopia's future energy security? What are the impacts of technological and efficiency innovation on the cost of energy production and the nation's energy mix?

3.1. Energy security indicators and measurability

Energy is an indispensable component of economic growth, either directly or indirectly, as an input in the production process that is a complement to capital and labour (Mulegeta et al., 2010). The use of energy for productive economic and social purposes, particularly among agro-processing industries, is a key driver of sustainable development. This means that energy, both as an input to production and an output from it, is a distinctive economic resource. As the lifeblood of industrialization, energy is required for all sorts of economic activities among all economic sectors. This helps create jobs and essential economic value in the process of extracting, transforming, and distributing energy. Ethiopia has targeted large-scale hydroelectric power as it accelerates green growth and boosting its export earnings. But this effort should reflect the economic efficiency of resource use, sustainability, and should also be cost effective.

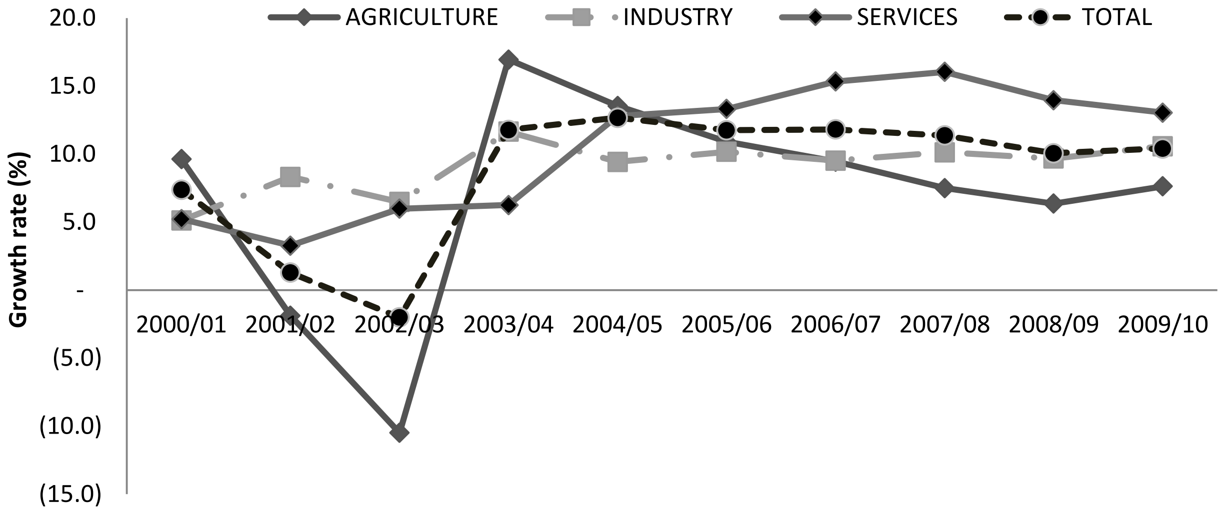

Figure 3.1. Annual economic growth rates by sector in Ethiopia, 1999–2009

Source: MoFED (2011)

It has been noted that the pace of global economic growth and rate of energy consumption are highly correlated (Ferguson et al., 2000; EEA, 2009). Statistics indicate that over the last ten years the Ethiopian economy has been growing steadily with a mean annual GDP growth rate of 8.6% (MoFED, 2011). The mean growth rates over the last decade varied across the three major economic sectors: 6.7% for agriculture, 9.2% for industry, and 10.7% for the service sector (Figure 3.1). Headcount poverty fell from 38.7% in 2004/05 to 29.6 % in 2010/11. Although the poverty level was reduced, the severity of poverty has changed little (MoFED, 2012).

Empirical research on the electricity supply strategy of Ethiopia using a CGE model has detected the impacts of electricity shortages on GDP growth (Engida et al., 2011). The results of this study implied that government imposed power rationing has resulted in a GDP loss of about 3.1%. In this study several general national energy security indicators and measures were identified. The major categories of security indicators in the context of the Ethiopian energy system are described in Table 3.1.

Table 3.1. Major energy security considerations in Ethiopia

FACTOR	INDICATOR
POLICY	
Energy diversification	Shares of different sources in energy production
Energy efficiency	Energy intensity, distribution, indoor air pollution
Clean energy access	Electrification rate
Renewable energy investment	Cost effectiveness
Governance	Effectiveness, coherence, degree of decentralization, etc.
Infrastructure	Reducing oil import dependence
Geopolitics	Export diversification, import substitution, employment, etc.
Economic growth	
ECONOMIC	
Affordability	Income, price, and expenditures
Competitiveness	Relative energy source costs
Cost effectiveness	Per unit cost of production
Economic diversification	Job creation, income diversification
Energy substitution	Cross-price elasticity
Market uncertainty	Price stability
SOCIAL	
Health, public well-being Food security	Pollution related mortality
Gender	Air pollution indicators (atmospheric CO_2 and CH_4 concentrations)
Sabotage and theft	
Tastes and preferences	Nutritional status
	Distribution of fuel collection by gender
	Frequency of theft and sabotage
	Energy consumer preferences
ENVIRONMENTAL	
GHG emissions	Levels of CO_2, CH_4, N_2O
Deforestation	Deforestation
Environmental degradation	Land degradation
Biodiversity	Biodiversity loss

Note: CH_4 = Methane, N_2O = Nitrous oxide

3.2. Overview of Ethiopia's energy sector: energy resource potential and consumption

Indigenous energy resource supply potential: Ethiopia is endowed with vast untapped supplies of a diversity of renewable energy resources. Currently, the country's energy needs are almost entirely met with hydroelectric power along with geothermal power and diesel power generation. A study by Ethiopian Economic Association (EEA) underscored that, in order to meet its growing energy needs Ethiopia faces management problems from both the supply and demand perspectives (EEA, 2009).

Non-renewable resources: Regarding fossil fuel potential there are no reliable quantitative estimates for Ethiopia. However, there are on-going exploration efforts. The federal government has indicated that the country possesses reserves of approximately 297 million m^3 of coal, 24.92 billion m^3 of natural gas, and 430,000 barrels (bbl) of crude oil (CIA, 2014), however, so far Ethiopia has not exploited these resources.

Renewable energy resources: Located in the tropics, Ethiopia has a diversity of potential renewable energy resources that could be harnessed for sustainable economic development. The country's energy needs have been predominantly satisfied by biomass fuels, which are consumed traditionally and inefficiently for residential needs. A considerable fraction of the country's renewable energy potential has not been exploited. Known exploitable renewable energy reserves and potential are described in Table 3.2.

Table 2.2. Current and potential or projected renewable energy resource capacity

Energy source	Unit	Potential reserve	Exploited	
			Amount	%
Hydroelectric	MW	45,000	2,100	5%
Solar	kWh/m^2/day	4–6		
Wind	GW	1,350	268MW	<3%
Geothermal	MW	5,000–7,000	7.3	<1%
Woody biomass	t (millions)	1,120	560	50%
Agricultural waste	t (millions)	15–20	≈6	30%
Municipal solid waste	t (millions)	2.8–8.8	50 MW (under construction)	

Source: MoWE (2013a), GMI (2011)

Hydroelectric power: Ethiopia is endowed with tremendous hydroelectric power generation potential with the continent's second-greatest water resources after the D.R. of Congo. Currently about 90% of the nation's electricity is generated from 11 hydroelectric power plants via an interconnected system (ICS). In addition, the Ethiopian Electric Power Corporation (EEPCO) has identified nearly 300 potential hydroelectric power generation sites on eight river systems, among which 102 have potential for large-scale generation capacity, while the remaining sites are considered appropriate for small-scale generation only. Large rivers make Ethiopia a potential hydroelectric power hub of East Africa. Recent EEPCO estimates of the potential hydroelectric power generation capacity of the country range from 45,000 MW to 153,000 GW. In 2010 the total installed annual capacity stood at 1,843 MW, or about 4.5% of the lower end of the of the country's hydroelectric potential range (Table A 3.1). Ethiopia has recently embarked on a process of developing multiple large-scale hydroelectric dams, the largest of which is referred to as the Great Ethiopian Renaissance Dam (GERD). This project has caused political tension between the country and some of its neighbours that are concerned about the potential for adverse effects on downstream water availability.

Geothermal power: Ethiopia is intersected by the GEARV, which offers promising geothermal energy generation potential. EEPCO estimated the exploitable geothermal power potential of the country at about 5,000 MW per year. Currently only one geothermal power plant (Alato Langano) is in operation with an annual capacity of 30 MW; however, it typically generates only 7.3 MW due to the intermittent nature of its operations. The country hopes to produce about 75 MW of power annually from geothermal sources by the end of the current 'growth and transformation plan' (GTP) in 2015 (MoWE, 2012). Recently the country signed a new geothermal development plan at a site called Corbetti Caldera in Oromia near the border with SNNP. Investment in geothermal power generation has been discouraged by cost-competitiveness with alternative sources that are associated with technological uncertainty, risks at the exploration and development stages, and limited availability of the necessary technical and skilled labour needs in the country.

Wind power: Ethiopia also has considerable wind energy potential, with an estimated annual capacity of up to 10,000 MW. Average wind speeds in the country vary significantly depending on location within a range of 3.5-5.5 meter/second for at least six hours per day (Bekele and Palm, 2010). Even though the country has no offshore prospects for developing wind power due to its landlocked geographical location, summer monsoons, tropical easterlies, and air current convergence over the Red Sea all contribute to extensive wind power potential (Mulugeta et al., 1996). The ability to harness wind power in remote off-grid areas also provides a cost-effective candidate for the electrification of rural villages. Recently the 51 MW Adama I wind farm was inaugurated in Oromia. Additional planned or operating projects include the 120 MW Ashegoda wind farm in Afar, the 300 MW Ayisha wind farm in Tigray, the 400 MW Debre Berhan Wind Park in Amhara, and the 153 MW Adama II and 100 MW Assela wind farms in Oromia (MoWE, 2012). National wind power policy is meant to complement hydroelectric power and help cope with the effects of erratic rainfall that impede hydroelectric power generation. As of today, about 268 MW of wind power capacity has been installed (MoWE, 2014). The current policy target is to generate 890 MW of wind power annually in the country by the end of the current five-year GTP in 2015 (MoWE, 2012).

Solar power: Due to its tropical geographic location and prevailing dry weather conditions Ethiopia also has considerable solar power generation potential. One feasibility study estimated Ethiopia's solar power potential at around 2,000 kWh/m^2 annually (Bekele and Palm, 2010). A recent estimate of the total annual solar power capacity of Ethiopia was 2.199 trillion MW hours (MWh) (MPWSE, 2012), with the northern part of the country having the greatest potential. Nevertheless the GTP has overlooked the potential contribution of solar power to the national energy supply. According to the current government development plan, solar power is expected to contribute a mere 30 MW annually by 2015 (MoWE, 2012). Very recently the Ethiopian Ministry of Water and Energy (MoWE) announced that it had awarded permission for the construction of three solar power farms with annual capacity of 100 MW each to the company 'Global Trade and Development Consulting' (GTDC) as part of the 'Obama Africa power initiative.' Solar energy is one of the most promising candidates for rural off-grid electrification. Cost competitiveness is major challenge to solar power exploitation, however, technical innovation, increased efficiency, and adaptability may play crucial roles in its future development and application.

Biomass and biogas energy: The country has diverse biomass energy resources, many of which are untapped, including: agricultural and related processing residues; forestry products such as fuelwood, non-timber forest product processing residues, and related processing waste; municipal solid waste; and switch grasses and other fuel crops. The country has 23 million hectares of land that are potentially suitable for biofuel development (MoWE, 2014). The country could use biodiesel driven from jatropha (*Jatropha caracas*) for rural electrification as it is a plausible candidate for decentralized rural community based systems. The country has also targeted the development of biogas power, including a 50 MW landfill gas project under construction in Addis Ababa.

3.3. Ethiopia’s energy resource diversity, energy mix, and energy security

The energy mix of Ethiopia has special features with regard to energy security. For instance, hydroelectric plants operate at full capacity during the rainy season (June-September), but are less productive during the dry season when power demand is typically higher because operating conditions are more favourable for schools, industry, and the services sector. Unlike hydroelectric power, solar and wind can be harnessed more reliably during the dry season. In contrast, biomass and geothermal power are available throughout the year. Exploiting the seasonal complementarity of this energy resource mix could be of paramount importance for long-term energy security and sustainable development. Recent energy storage technology innovations make it possible to store power generated from intermittent sources like wind and solar more effectively, however, construction of the required facilities would be expensive. Specific advantages and disadvantages of different renewable energy resources of the country are summarized in Table 3.3. The major problems of energy supply security were identified as:

- Dependence on oil imports, which exposes Ethiopia to price volatility
- Centralized large-scale hydroelectric power, which is expensive and presents infrastructure challenges for reaching remote off-grid areas
- A general lack of energy infrastructure, rugged topography, and highly scattered rural settlements
- Sporadic power shortages due to drought
- Environmental problems associated with unregulated biomass energy collection and utilization, such as deforestation, forest fragmentation, and indoor air pollution
- Energy efficiency problems and gender inequities related to traditional biomass use
- Adverse health effects due to poor emission control of fossil fuel combustion and IAP associated with inefficient residential biomass combustion

Table 3.3. Overview of renewable energy resources in Ethiopia

ADVANTAGES	DISADVANTAGES
BIOMASS	
• Cost competitiveness or effectiveness • Variable and highly availability • Diversity of types and sources • Suitable for substituting fossil fuels • Labour intensive (i.e. high job creation and poverty mitigation potential) • Synergistic linkages between agriculture and industry • Greater distribution/access relative to fossil fuels • Less geopolitical vulnerability than fossil fuels • Predictable and stable supplies • Diverse organic based products • Generation of organic fertilizer as a by product • ‘Carbon neutral’[5]	• Lower net energy content relative to fossil fuels • Environmental externality risks (i.e. sustainability) • Food security threat risk (i.e. food vs. fuel debate) • Resource constraints (i.e. water, land and labour) • Coordination of heterogeneous groups along supply chains required • Traditional use poses health threats
HYDROELECTRIC	
✓ Abundant resource ✓ May facilitate regional integration ✓ Cheap generation cost due to plant longevity ✓ Convenient for power exports	✓ Vulnerability to drought ✓ Potential source of regional political tension/risk ✓ Negative downstream impacts ✓ Massive capital investment needs for transmission infrastructure ✓ Less suitable for off-grid use ✓ Energy vs. agricultural water use conflict (i.e. food security implications)
WIND and SOLAR	
• No effect on food security • Creates jobs for local economies • Low or no risk of environmental externality • No fuel costs	• Expensive infrastructure • Intermittent supply (i.e. additional costs for effective storage facility) • Limited applications
GEOTHERMAL	
o High job creation potential o Very low risk of negative environmental impacts o Stable power generation	o Limited geographic distribution o High cost of exploration and development

3.4. Power production sources

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[5] ‘Carbon neutrality’ depends on the net emissions in the lifecycle of bioenergy production, processing, and consumption. The net impact on GHG emissions depends on the effects on forest and land change due to the carbon sequestration effects of plants. The use of certain wastes such as municipal solid waste and industrial biodegradable waste is expected to have net positive GHG impacts.

In 2010 Ethiopia had an installed annual capacity of about 2,043 MW (EEPCO, 2011). Ethiopia's electricity generation over the 2000-2010 period is presented in Figure 3.2. Diesel electric generators are frequently used by industrial, commercial, and service sector actors to compensate for regular power shortages and government imposed power rationing. EEPCO's self-contained system (SCS) is based on diesel-powered generators. The country responded to power shortages over the period 2007-2009 by increasing diesel thermal systems (Figure 3.5), which claimed the decade's highest percentage share of about 11% due to the effects of extended drought (Figure 3.2). Private use of diesel generators was not included in the evaluation. The historical pattern of power resource development over the 1961-2010 period is presented in Table A 3.1.

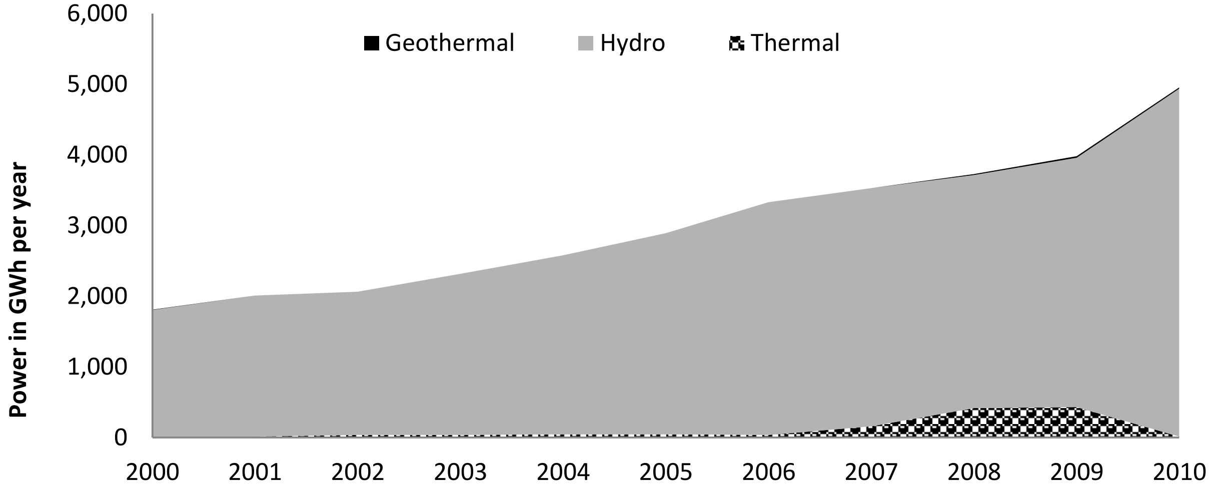

Figure 3.2. Ethiopia's electricity generation by source (GWh per year), 2000-2010
Source: EEPCO (2011)

Installed hydroelectric power capacity expansion over the last four decades is depicted in Figure 3.3. There was a sharp rise in installed capacity expansion beginning in 2004. Annual capacity rose from about 663 MW in 2004 to about 1,843 MW in 2010 (178% increase). There are many new hydroelectric power plants planned or under construction, but the underdeveloped transmission and distribution network infrastructure continues to be a challenge.

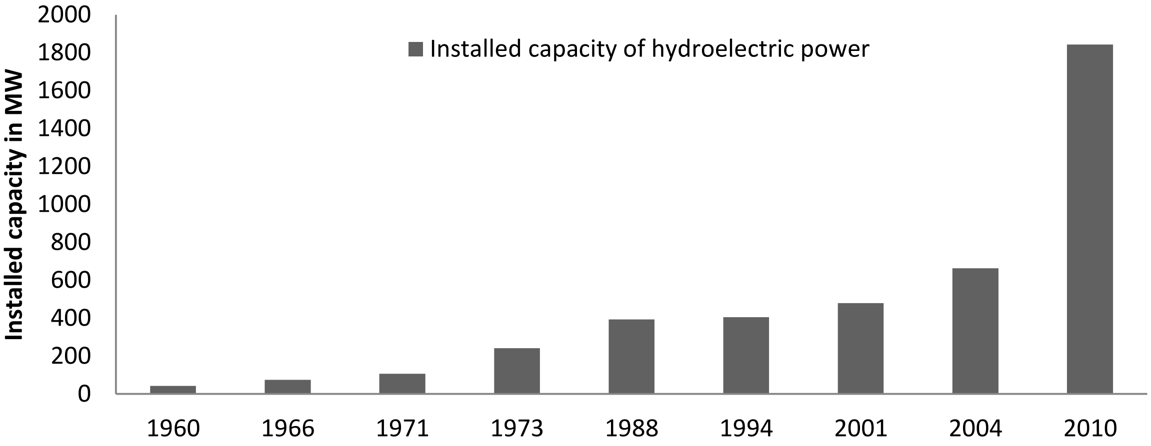

Figure 3.3. **Installed hydroelectric power capacity in Ethiopia over time, 1960-2010**
Source: EEPCO (2011)

3.5. Energy consumption

The MoWE reported that the total national energy consumption in 2010 was 1.3 Exajoules. In that year energy consumption was dominated by residential use (87%), followed by the transportation (8%), combined commercial and services sectors (5%), and the remainder (1%) was used by the industrial sector. Annual energy production in Ethiopia was equivalent to 29.581 million tonnes of oil and consumption was equivalent to 30.02 million tonnes of oil in 2010, with the balance provided by imported petroleum products (Table A 3.2). An overwhelming share of the energy consumed by Ethiopia in 2009 (92%) was derived from biomass sources, fossil fuels accounted for 7%, and other forms of electricity generation were only 1% (IEA, 2009). In terms of end users, about 92% of the energy was consumed for residential use, followed by transportation (4%), industry (2%), and commerce (1%). The greatest share of petroleum consumed was by the transportation sector (61%), followed by industry (25%), and residential use (14%). Approximately equal shares (38%) of electrical consumption were represented by the industrial sector and residential use, the balance (24%) was consumed by the commercial sector and public utilities. Biomass energy was entirely consumed for residential purposes (99%), except for 1% that was consumed by commercial and public services (Figure 3.4).

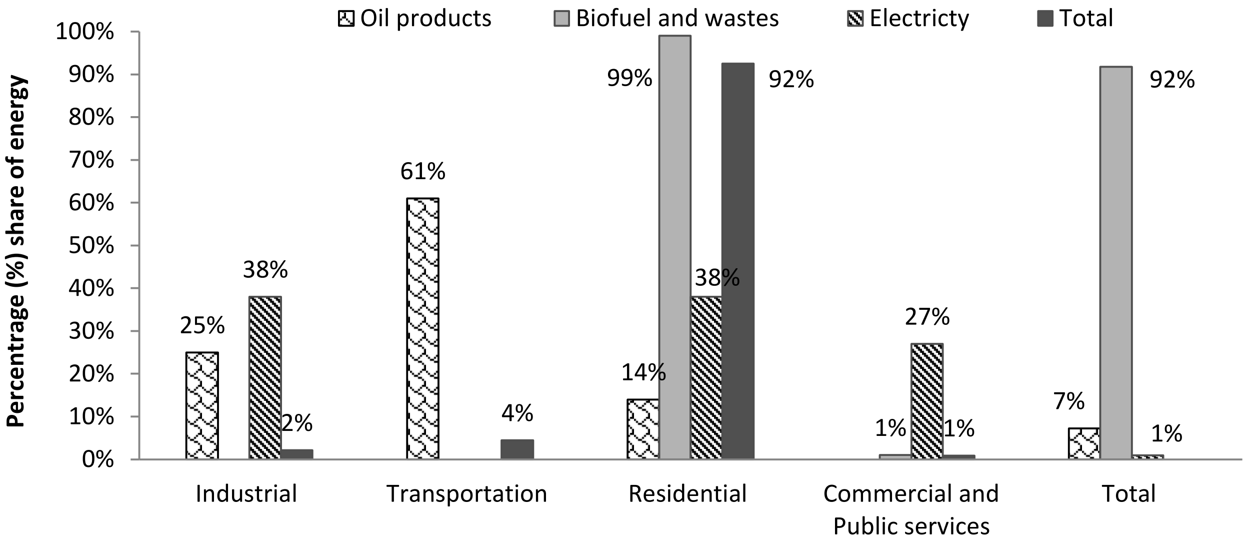

Figure 2.4. Distribution of energy consumption in Ethiopia by end user, 2009
Source: IEA (2009)

3.5.1. Electricity consumption

Figure 3.5 shows the trends in electricity consumption by different sectors over three decades (1981–2011). The main electricity user in 2011 was the residential sector with a share of 38% (1.47 Terawatt hours [TWh]), followed by the industrial sector with a share of 36% (1.4 TWh), and the combined commercial and public sectors with a 24% share (0.94 TWh).

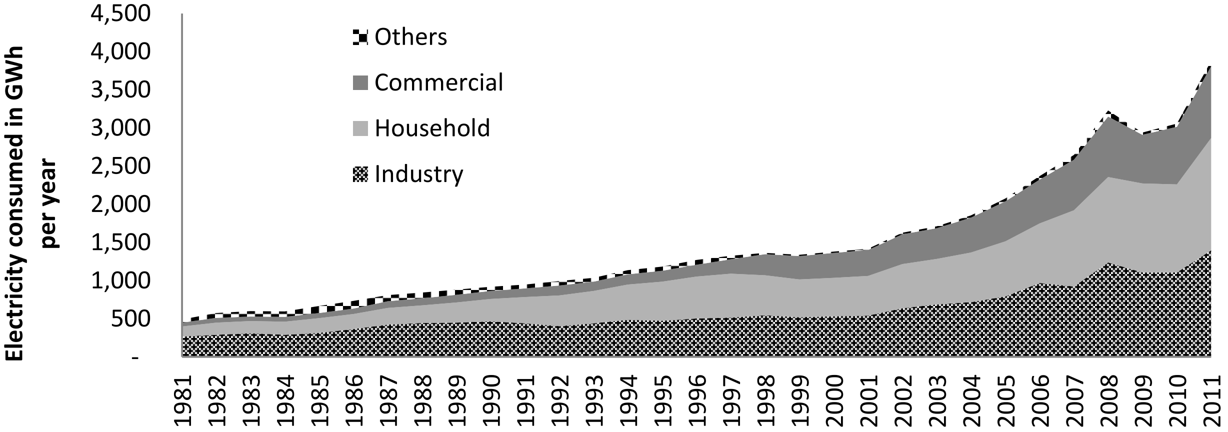

Figure 3.5. Trends in electricity consumption in Ethiopia (kWh per year) by end user sectors, 1981-2011
Source: EEPCO (2011)

The largest share of mean electricity consumption over the three decades was consumed by the industrial sector (43%), followed by residential use (35%), and combined commercial and public sectors (17%). The balance (5%) was used for miscellaneous activities like street illumination, EEPCO internal consumption, etc. In 2011 Ethiopia began exporting power (17 GWh/year) to Djibouti, which represented about 0.4% of the total power consumed (EEPCO, 2011). Over time the annual percentage share of electricity used by the commercial sector increased significantly within a range of 10-25%. The residential electricity use share also increased, with a range between 27% and 43%. Even though electricity use by the industrial sector is still high, proportionally it has dropped significantly (from 55% to 36%). A similar trend was observed for electricity use for other purposes.

In order to sustain its growing economy Ethiopia should invest in sustainable energy to keep pace with the unprecedented growth in energy demand. National statistics indicate that high economic growth over the past decade had a high correlation with increased fossil fuel demand; however, dependence on imported oil places a formidable constraint on the economy. This is demonstrated in fiscal inflationary pressure experienced by the country that accompanies high oil price volatility. Demand for oil has been growing at a high rate (Figure 3.6). During the entire period from 2005 to 2010 oil imports increased by about 34%, growing at an mean annual rate of about 7%. As a result the biofuel agenda remained on the top of Ethiopia's energy policy agenda as the country seeks substitutes for fossil fuel imports.

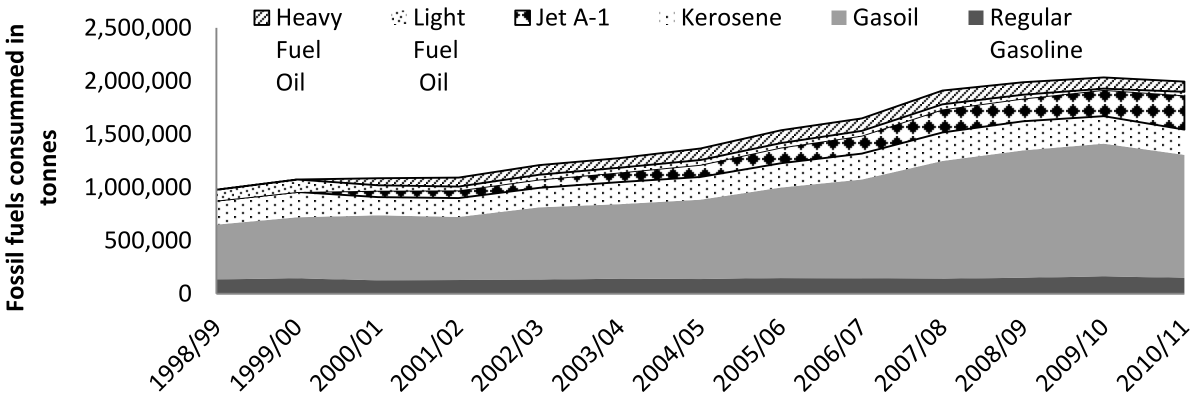

Figure 3.6. Ethiopia's petroleum product consumption (tonnes), 1991-2011
Source: EPE (2011)

Energy generation from indigenous sources was entirely dominated by biomass and hydroelectric power (Table A 3.2). Changes in the national energy mix included the share of primary biomass declining slightly from 93% to 89%, and the introduction of ethanol or derived biomass representing 3% in 2010. The share of electricity remained low at about 1%, while share of petroleum products increased from 6% to 7%. In terms of the distribution by end user: residential use accounted for 93%, followed by transportation with about 6%, and the balance of 2% was shared equally between the industrial and others sectors (Table A 3.3). Ethiopia's energy balance reflects a diversity of energy and production sources, imported oil types, and energy consumption by sector.

3.5.2. Biomass energy consumption trends

Biomass energy has many important features of interest with respect to energy security in developing countries. It is often the backbone of the energy system in such economies and considered the only subsistence energy source for the poor. In general, there are two types of biomass energy. Biomass energy resources may be traditional, which are minimally processed and often referred to as solid biomass because the most common forms are fuelwood, traditional charcoal, and agricultural fuel; and modern biomass energy sources such as charcoal briquettes, biodiesel, bioethanol, biogas, electricity, etc. The trends in traditional biomass energy consumption in Ethiopia are depicted in Figure 3.7. Traditional biomass use is the most common form of energy consumption in Ethiopia. The country has prioritized transportation biofuel development as a measure of reducing dependence on fossil fuel imports, mitigating climate change, and improving economic competitiveness.

The total quantity of traditional biomass energy consumption increased from 0.93 million Terajoules (TJ) in 1999 to 1.22 million TJ in 2010, reflecting an annual rate of 2.5%. Fuelwood was consumed only for residential purposes. The mean percentage share of rural household fuelwood consumption over the decade was about 91% and the balance (9%) was attributed to urban household use. Out of total biomass consumption for the decade the mean share of fuelwood was about 76%, and the remaining biomass consumption of the country was derived from agricultural residues (i.e. dried cattle dung and crop residues) with a 22% share and charcoal with 2%. Comparing the second half of the decade to the first half (1999-2005), the percentage shares for fuelwood and agricultural residues each declined by 1%, which was accompanied by a 2% increase in the share of charcoal consumption. Charcoal was mostly consumed by households (97%), followed by the commercial sector and public utilities (3%). An increasing trend in charcoal consumption by urban households is also expected as a substitute for fuelwood as income grows. But this increases pressure on forests because charcoal production is inefficient with respect to fuelwood resources; however, the introduction of densification or briquette technology offers a more efficient option.

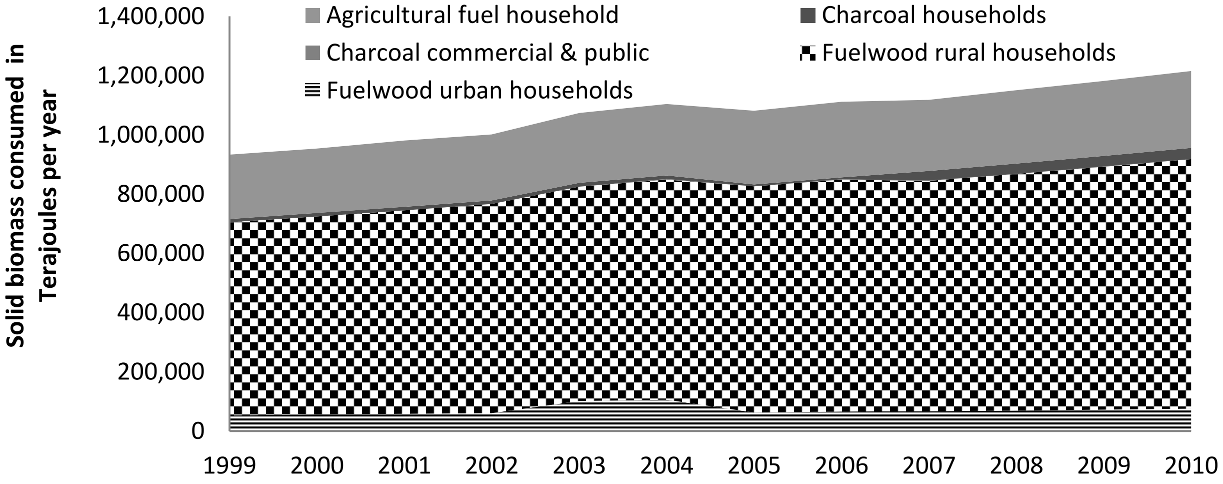

Figure 3.7. Biomass energy consumption trends in Ethiopia, 1999-2010

Source: MoWE (2010a)

3.5.3. Energy consumption by sectors

The sectoral distribution of energy consumption by end user for the 1999-2005 period is described in Table A 3.4. The mean share of industrial sector use for the decade was about 37%, followed by residential use (34%), and the service sector (23%). The mean annual growth rate of power consumption was 10% for the industrial sector and 11% for the service sector and residential use combined.

Residential use: According to the World Bank (2013b) annual per capita electricity consumption of Ethiopia in 2012 was about 52 kWh. Residential electricity use accounted for 38% of total electricity consumption. Residential electricity consumption is mainly for illumination purposes. Residential energy consumption comprises about 92% of the aggregate energy use. Almost all of the solid biomass energy (about 99%) was consumed for residential purposes. The main purposes of biomass energy use by the residential sector are subsistence uses such as cooking and heating.

Commercial and services: The commercial and service sector includes educational institutions, commercial or trade centres, banks and financial institutions, and private institutions and businesses. Ethiopia's commercial and service sector is growing at a faster rate than other sectors due to increasing investment in hotels and tourism. Energy consumption in the commercial and service sector is for illumination, refrigeration, space and water heating, and operating office equipment. Energy use by this sector comprised a small fraction (1%) of aggregate energy use in 2009, representing about 24% of electricity and 1% of biomass energy. The percentage share of energy consumed by the sector increased to 5% in 2010 (Figure 3.3).

Industry: Energy use by the industrial sector includes applications for processing steam, mechanical, machine and motor operation, and heating boilers and furnaces. This basically involves the use of energy for producing goods and services, which supports economic growth. The industrial sector consumed only 2% of the total aggregate energy consumption, which represented 38% of electricity and 25% of oil consumption.

Transportation: In any economy the transportation sector is an engine for economic growth. But it is also a main contributor of carbon emissions because in most economies the sector relies entirely on fossil fuels. In the case of Ethiopia, vehicles are often old and energy inefficient, causing even more pollution. The importation of modern, energy efficient vehicles into Ethiopia is discouraged by high tariffs. The sector relies heavily on imported petroleum products. In 2009 about 61% of Ethiopia's petroleum consumption was used by the transportation sector. As a result the federal government of Ethiopia began encouraging ethanol/diesel blends in 2008, which started with E_5 (a 5% ethanol, 95% diesel blend) mandates in the capital. This was upgraded to an E_{10} mandate as of March 2010. The MoWE (2014) indicates that these measures have saved the country US$ 24 million. The current plan is to increase the blending mandate to 25% bioethanol by 2025. Another main driver of bioethanol demand in Ethiopia is on-going railway expansion, which is expected to use biofuel and enables the country to expand its sugar industry.

Agriculture: Mechanized agriculture in developed countries uses energy for a variety of purposes such as irrigation pumps, fuel for machinery and tractors, etc. In Ethiopia, agricultural production is dominated by primitive technologies practiced by small–scale producers. The main sources of energy in the agricultural sector are therefore manual labour and draught animals, with only limited use of modern energy resources. However, with the growing need for investment in agricultural transformation and technological innovation, the energy needs of the sector are expected to increase substantially in the future.

3.6. Ethiopia's energy system: framework of existing energy use and prospective contributions of renewables to future energy security

In order to assess future energy security and the potential contribution of renewable energy technology to it, a comprehensive understanding of the energy system was essential. There is an intricate network of interrelationships within Ethiopia's energy system, which is one of the major pillars supporting the social, economic, and environmental sustainability of the national economy. The concept of an energy system or energy balance encompasses energy resources, energy importation and exportation, inputs and outputs of the energy sector (i.e. how energy resources are converted to electrical power), technological conversion pathways, and the final energy consumers. The existing and prospective energy systems of Ethiopia are described in Figure 3.8.

There are number of evolving technical innovations for biomass based generation of modern energy forms that are cleaner than traditional fuels. These include gaseous, liquid transportation fuels, and electricity alternatives that have broader application potential. This reflects the unique ability of bio-based energy to replace fossil fuels among all end users. Except for under certain conditions where electrical power is used with new electric vehicles and a few other very recent innovations, sources of energy other than biofuel and biomass play minimal roles in replacing fossil fuels. Biomass can now be used for the production of all forms of energy utilized by all economic sectors.

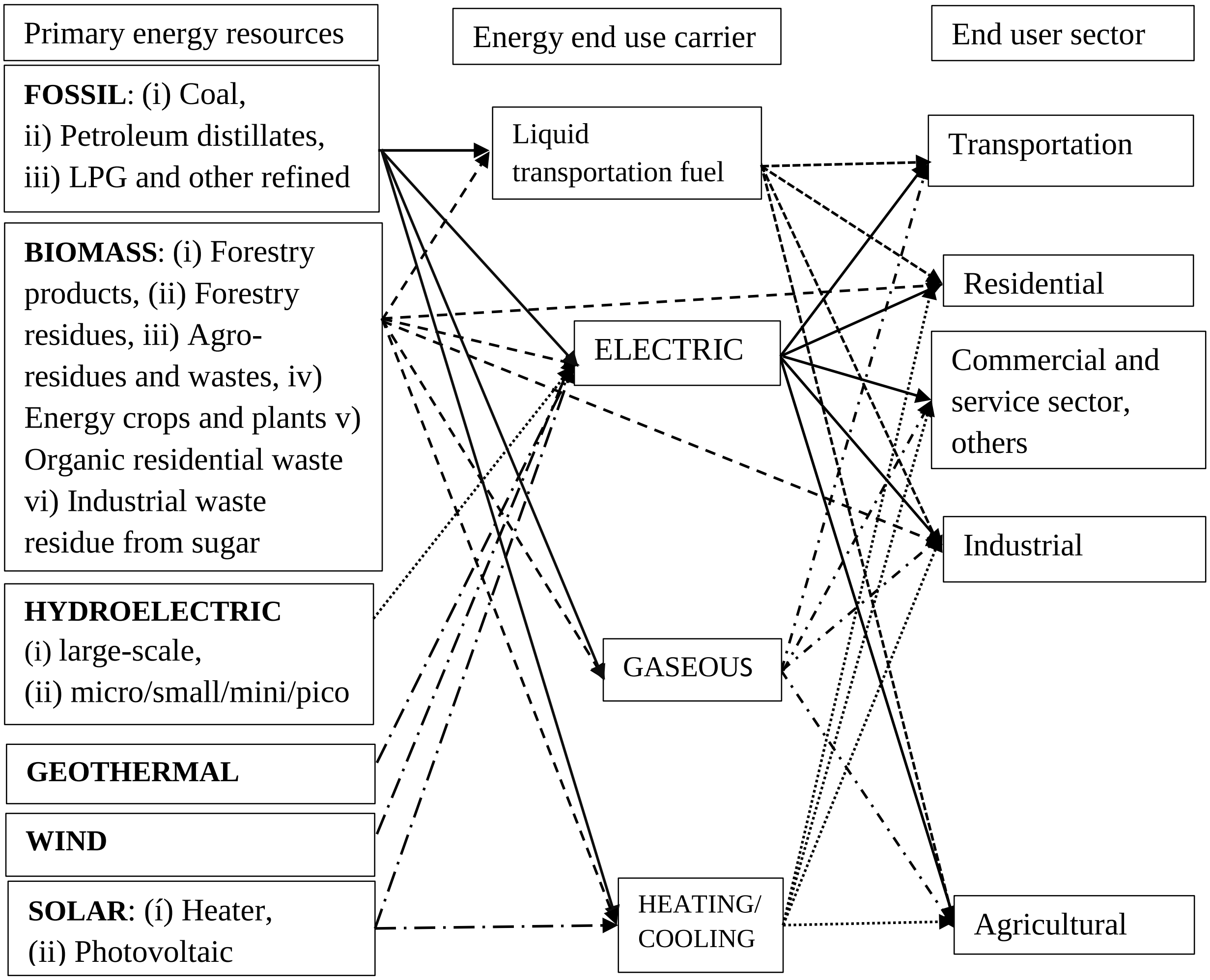

Figure 3.8. Diagram of Ethiopia's energy system

3.7. Bioenergy demand and prospective development applications

With growing interest in exploiting opportunities, bio-based fuel technologies are increasingly expanding worldwide. Productive, sustainable and efficient use of biomass in advanced forms has huge potential for the production of more convenient commercial energy (Larson and Kartha, 2000). There are various estimates of the contributions of global biomass energy to energy–mix portfolios. Biomass energy accounted for roughly 10% or 50 Exajoules (EJ) of the total global primary energy supply (TPES) in 2009 (IEA, 2012). In combination with ubiquitous and inefficient use of biomass by millions of poor people in developing countries, this has brought the issue of generating modern energy from biomass to the forefront of sustainability challenges. Rapid growth in the global demand for modern bio-based energy is linked to several new demand and supply related factors. The main contributors are:

- continually increasing demand for fossil fuels;
- the role of bioenergy in rural development and poverty alleviation;

- substitution for fossil fuels to reduce GHG emission;
- public health risks arising from indoor emissions due to inefficient biomass combustion;
- health risks posed by outdoor air pollution from fossil fuel use;
- the need for modernizing inefficient and unsustainable traditional residential biomass use;
- the increasing demand for secure, safe, and accessible food, fodder, and energy
- rapid population growth, rising income, and diminishing resource bases and the need for green growth that depends on renewable resources,
- scientific advancements and technical innovations in the processing and recycling of waste into clean energy

(Schlamadinger et al., 2006; Langeveld et al., 2010; Guta, 2012b; von Braun, 2013)

A major challenge to modern biomass energy development is cost competitiveness with other power sources, particularly fossil fuels. Brazil has been able to produce sugarcane based bioenergy competitively with fossil fuels (Rosegrant et al., 2008; Pereira et al., 2012). Ethiopia has considerable biomass resource potential that can be harnessed with the aid of innovative technologies. It has been argued that “Ethiopia could be considered as a typical country in Africa where a real challenge is to modernize bioenergy systems and ensure that the developments of industries around bioenergy are sustainable and profitable” (McCormick and Willquist, 2013). Biomass energy is also viewed as a promising part of poverty alleviation efforts due to labour intensiveness and associated links to rural livelihoods, although there is also potential for negative effects.

3.7.1. Types of modern bio-based energy and their prospects for application in Ethiopia

Biomass charcoal briquettes: In Sub–Saharan African countries, including Ethiopia, the typical methods used for making charcoal are inefficient in terms of the amount of biomass material wasted in the process. Charcoal briquettes are used for residential cooking and heating purposes, for small–scale craft industries like blacksmithing, and some industrial applications. Biomass briquettes can be produced from various biomass resources, including: forestry residues, straw, organic waste products such as sawdust, rice husks, banana peels, ensete residues, sugarcane stalks, and the leaves of eucalyptus and other trees, cotton husk, coffee pulp, maize residues, wood processing residues, and bamboo plants.

China and India have made considerable progress in improving these methods through the use of bio–briquettes. In Ethiopia biomass briquette technology has only been recently applied. A factory has begun production of briquettes, primarily from coffee pulp, in SNNP (Hawasa), while another is under construction in Addis Ababa. There is huge market potential for charcoal briquettes, as they are often preferred over traditional charcoal and fuelwood. Stove technology for using them for baking traditional foods such as *enjera*, however, is underdeveloped.

Biomass power: Globally, biomass power generation has been expanding rapidly. For instance, current EU policies are expected to lead to nearly double the amount of annual electricity generation from biomass, from 22,506.44 MW in 2010 to 43,274.04 MW in 2020 (Jäger-Waldau et al., 2011). Two principal technical conversion processes may be used to generate electricity from biomass: (i) direct conversion using technologies like co–firing, LFG, and others; and (ii) indirect conversion through replacement of diesel with biodiesel. Biomass resources like wood, organic wastes, and other biomass residues can all be used for co-firing. The technology has been implemented for a broad spectrum of purposes, such as cement production, iron smelting, and residential heating. There are several advantages offered by biomass co-firing technology. The use of waste from forestry and agriculture will increase the economic value of biomass power, which is usually more accessible in energy deprived rural areas.

Combined heat and power (CHP) is another promising technology for biomass power generation. An important benefit of CHP in the case of Ethiopia is the possibility for substituting biofuel feedstock for fossil fuels, as CHP plants can use diesel gas or engine biofuels. This provides an opportunity to displace fossil fuels with cleaner biofuels in a cost-effective manner. Ethiopia has the potential to produce 1.11 million tonnes of bagasse per year (ISO, 2009). Ethiopia is producing cogeneration electricity in existing sugar factories (Metahara, Wonji/Shoa, and recently Fincha) to meet the power needs of factories with the objective of expanding capacity to feed power into public grids. Recently the country is investing significantly in large sugar factories to increase sugar, ethanol, and CHP generation as part of its biofuel policy.

Such an effort could potentially displace diesel used in decentralized SCSs. For instance, sugar factories could supply power to surrounding residential areas. The power generated could also be fed into the national grid or an ICS. There is also potential for innovation and efficiency gains through integrating system components. The European Commission (2004) indicated that pyrolysis based electricity generation can produce 100 kWh of electricity and 50 kWh of heat from one tonne of biomass. That report described three stages of the process: (i) biomass conversion to bio-oil through pyrolysis, (ii) bio-oil conversion to hydrogen (H_2) or carbon dioxide (CO_2) using catalytic processes, and (iii) the final conversion of gaseous fuel to green electricity in a fuel cell.

Biogas: Biogas is generated from a combination of four factors: organic material, heat, bacteria, and anaerobic conditions (House, 2007). Biogas was introduced to Ethiopia several decades ago. Until recently, however, biogas remained a negligible portion of overall energy production. As part of the rural clean energy supply strategy, the National Biogas Programme of Ethiopia (NBPE) was established in collaboration with the Netherlands Development Organization (SNV) and the Ethiopian Rural Energy Development Centre (EREDC) to support biogas expansion in rural Ethiopia. The programme offers a package that includes orientation and technical training, and a subsidy that covers one-third of the upfront capital investment costs. The objective of the programme was to construct 14,000 biogas digesters by the end of 2013, which was hoped to help the country reach 1.4% of the estimated potential in four major regions: Oromia, Amhara, SNNP, and Tigray. That study estimated that there is potential to install about one million biogas digesters in these four regions of the country alone.

A diversity of biomass feedstock options can be used for biogas anaerobic fermentation, including: most biomass resources, slurry from diary production, and some industrial and municipal wastes. In many African countries rural energy interventions have focused on the use of small-scale biogas digesters, which are used to supply clean energy to households in off–grid areas. Ethiopia has the largest livestock population in Africa and ranks among the top five livestock producing countries in the world today. Though the country's current rural energy policy emphasizes biogas, it is underdeveloped due to various factors such as technical barriers, financial and availability constraints, poor performance of some existing biogas digester designs, and a lack of appropriate energy for many end-use applications.

Biogas can play a vital role in alleviating rural energy problems and improving gender equity issues associated with traditional biomass energy use such as public health, and environmental externalities. Furthermore, organic fertilizer is derived from biogas production that can be used to enhance farm productivity and food security. Many developed and emerging economies have effectively developed biogas potential. Ethiopia could explore alternative policy measures for realizing the potential of biogas.

Landfill gas capture: With rapidly growing urbanization in many African countries, including Ethiopia, the management and disposal of municipal waste have become growing problems. The disposal of municipal waste is increasingly a cause of public and environmental health problems. Landfill gas (LFG) capture is a technological innovation that economically and efficiently generates clean power and mitigates urban waste and air pollution problems through the use of organic waste (UNEP, 2009; 2011). LFG technology relies on anaerobic decomposition processes that capture LFGs from organic waste and convert it into useful forms of energy like electricity that can be used directly or fed into a grid. The main benefit of LFG is that it can be used to collect CH_4 from organic municipal waste and use it for energy production. LFG technology is an important energy production option for Ethiopia because it can help reduce the emission of GHGs, reduce urban environmental waste/pollution, and create employment related to the operation of LFG capture systems (UNEP, 2009). There is currently an LFG capture system under construction in Addis Ababa with a projected installed capacity of 50 MW.

Biodiesel: Biodiesel is one of the most promising modern biofuels. It can be used to blend with fossil diesel for transportation fuel. The current annual GTP target is the production of up to 1.6 million litres of biodiesel by 2015. The use of castor bean for energy in Ethiopia is not new, it has been used to produce oil for illumination purposes since ancient times. Castor oil is used for the traditional preparation of *enjera* stoves. Castor bean is also used for the production of important products such as medicines, lubricants, and cosmetics. A diversity of food crops such as maize, oil palm, soybean, sugarcane, and others have potential for biodiesel production, while non-food crops for biodiesel include switch grasses, castor bean, tobacco, and jatropha. However, the potential food vs. fuel conflict from the use of food crops for biofuel generation has been intensely debated, while the use of non-food crops may also have negative side effects such as competition for agricultural resources.

Ethiopia has tremendous potential for generating biodiesel from crops, crop wastes, and livestock wastes. Biomass feedstocks options include: (i) oilseed bearing plants such as castor bean, jatropha, and oil palm; (ii) vegetable oils from crops such as olives, sunflower, soybean, tobacco, rapeseed, and others; and (iii) abundant livestock waste fat. The national energy policy has emphasized the promotion of jatropha, an inedible plant, for biodiesel production, however, there are many sustainability concerns about mass production of this crop.

There are many other waste–to–biodiesel conversion technologies. For example, the use of livestock fat waste as methyl ester blends with diesel (Gürü et al., 2009) has emerged as one of the most promising technological options. In this aspect Ethiopia has a competitive cost advantage because livestock fat waste has limited alternative economic uses (soap manufacturing). This application avoids fuel vs. food security conflicts.

Bioethanol: Globally, ethanol blending with gasoline for use as automobile fuel and residential cook stoves has attracted considerable attention (Datar et al., 2004). This is because of decreasing fossil fuel reserves, volatility of gasoline prices, and the environmental externality costs of fossil fuel use have necessitated the search for alternative biofuels (Canilha et al., 2012).

Ethiopia began blending gasoline with ethanol in 2009 for the domestic market to save money used for oil imports. The current GTP target is to increase annual ethanol production to 194.9 million litres in order to raise the ethanol content in transportation fuel blends from the current 10% to 25% by 2015 (CRGE, 2011). The government has also targeted ethanol use in stoves that can serve as substitutse for kerosene and traditional biomass stoves for residential energy use. The MoWE (2014) indicates that over the last two-and-a-half years of the current GTP the country blended about 33.94 million litres of ethanol from the sugar industry, which has enabled the country to save more than US$ 26.74 million.

Ethiopia’s ethanol generation is currently based on sugarcane, sugar beet, sweet sorghum, and other crops. Experience from other African countries shows that ethanol can also be generated from cassava. Cassava is a well-known food in southern Ethiopia, but is not used in other regions. The Ethiopian Ministry of Agriculture (MoA) has begun to promote more widespread use of cassava to enhance food security. Greater use of cassava for ethanol production will also be an opportunity to contribute significantly to the welfare of the poor for energy security.

Biobutanol: Biobutanol is produced from biomass or cellulosic biomass through a process known as ‘acetone-butanol-ethanol (ABE) fermentation’ and offers an attractive substitute for fossil fuels for the transportation sector (Blaschek et al., 2007). Biobutanol can be generated from various cereal crops, sugarcane, and sugar beet. Compared to ethanol, butanol has three distinctive advantages: (i) higher energy content, (ii) it is less corrosive, and (ii) it more easily fitted to and transported through existing oil distribution pipelines (Nigam and Singh, 2011). Biomass-based butanol can be blended with gasoline at a ratio of 85:15 and used in ‘unmodified gasoline engines’ (Wu et al., 2007). However, many important issues are under scrutiny to make biobutanol competitive in terms of production costs.

Biomethanol: Biomethanol is among the most promising transportation biofuels. It can be produced through gasification technology from forestry residues, wood, solid organic municipal and industrial waste, and other biomass feedstock (UNEP, 2009; IRENA, 2013a). Biomethanol provides a promising opportunity for countries like Ethiopia to harness forest resources more sustainability. Ethiopia is in the process of changing communal forest property rights to cooperative user systems. There is potential for creating forestry product value chains that integrate modern biomethanol production in a cost-effective manner, but policy measures are needed to help address several barriers. For instance, one technical study indicated that the commercial application of biomethanol is inhibited by high production costs and capital investment required (IRENA, 2013a). That report also suggested that further advancements in gasification technologies could improve the economics of biomethanol production.

Pyrolysis gasoline or syngas: Syngas is obtained from carbon containing resources like coal and the gasification of biomass resources including municipal waste (Demirbas, 2008; Shah et al., 2010). In terms of its main constituents, syngas contains carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and other gaseous hydrocarbons and its production yields by-products that have high market value (Demirbas, 2008). Syngas would add to the diversity of Ethiopia's energy mix because it can be consumed by a broad spectrum of end-users and produces chemicals for other uses. Greater syngas production capacity would benefit Ethiopia and other African countries due to the feasible application of the technology and the availability of suitable biomass resources as required raw materials.

3.7.2. Sustainability dimensions of bio-based energy

The feasibility of biomass use for generating modern forms of energy is determined by various factors, such as the availability of feedstocks and various political, social, and economic aspects. A major challenge arises at the feedstock procurement stage that is directly or indirectly linked to the livelihoods of small-scale and often poor agricultural producers. The problem is largely associated with large-scale bioenergy investments, but the relative shadow prices of resources that can be used for biofuel and agricultural activities, as well as the interactions among market, social, institutional, technical, economic, and environmental factors, will together determine whether it is possible or not to expand biofuel production.

3.7.2.1. Political aspects

Political institutions play a crucial role in sustainable bioenergy development. This is particularly true for large-scale biofuel initiatives in countries where land tenure is insecure. Like any other potential investment activity, investment in biofuels requires a stable political environment. Appropriate incentives are required to attract biofuel investment, but regulating the negative effects of the industry on local environments and conflicts with social interests over resources requires strong policy design and implementation. It is also important for political systems to create appropriate policies, institutions, and regulations, and to assure the availability of necessary infrastructure, which is typically inadequate in Africa. More importantly, investment in R&D for the integration of technological innovation into biofuel value chains is critical for achieving similar successes in other countries. Ethiopia can learn from the success of Brazilian ethanol development where state intervention played vital role in the establishment of the necessary infrastructural, design, and implementation (Hira and Guilherme de Oliveira, 2009).

A previous study in Ethiopia identified barriers in demand and supply factors, technological aspects, and institutional bottlenecks that impede modernization of the bioenergy sector (Guta, 2012b). The federal government has expressed its desire to work towards the development of sustainable biofuels and entered into discussions with the ‘Roundtable on Sustainable Biofuels’ on how to improve the current regulatory system and ensure that biofuel investments and development are on a path towards improved sustainability (McCormick and Willquist, 2013). Hence, governmental institutions have key roles to play in harnessing the benefits of bioenergy and addressing associated economic, social, and environmental risks.

3.7.2.2. Economic aspects

Economic aspects are crucially important for the assessment of bioenergy sustainability. The volatility of food and fuel prices in recent years and the following global economic and financial crises pose threats to bioenergy sustainability. Since the global food price inflation peak of 2008 there has been an on-going debate about biofuel production and food security. Poor nations are particularly vulnerable to the consequences of food price volatility. Large-scale biofuel initiatives may displace food producing farmers or motivate them to switch production systems to non-food crops, which in turn may lower agricultural productivity and threaten food security. According to von Braun and Pachauri (2006), “biofuels have a high place on the global agenda, largely due to energy security, higher energy prices, and increasing concerns about global climate change, as well as the income expectations of farmers and other investors.” Another study evaluated the economic and environmental impacts of Taiwanese agriculture from producing renewable biomass energy (Chen et al., 2011) using an agricultural sector model and found that such a strategy can increase farm revenues, rural employment, energy self-sufficiency, and reduce GHG emissions, but can also increase government expenditures. Biomass for energy generation may compete with food crop production for agricultural land and water, especially in developing regions (von Braun and Meinzen-Dick, 2009). This may cause changes in the shadow prices of resources and have negative local livelihood consequences.

Another study in Ethiopia identified how large-scale biofuel initiatives for biodiesel and ethanol production might achieve ‘win-win’ outcomes that could improve small-scale productivity (food security) and increase household welfare (Gebreegziabher et al., 2013). That study applied a CGE model and found that when the spill-over effects of large-scale biofuel projects are considered, not only does the welfare of poor rural households improve, but that urban households also benefit from returns on labour under some scenarios. That study also noted that biofuel investments on “unutilized land” were associated with increases in both cereals and cash crops production without increasing cereal prices, however, the effects varied geographically. It should be noted that global biofuel, petroleum and food price trends are more relevant for countries like Ethiopia that are net food and energy importers.

Other major economic factors that affect the sustainability of bioenergy are market constraints. A report by the FAO (2013) indicated that the biofuel industry has the potential to create and improve market mechanisms such as rural physical infrastructure, which can moderate prices and create ancillary benefits in the form of the emergence of agribusiness opportunities and the advancement of rural institutions. Biofuel investments can contribute significantly to poverty reduction and rural development by creating job opportunities and clean energy options. Developing modern bioenergy potential such as the production of biogas, bioethanol, and biodiesel, as well as broader use of improved efficiency biomass stoves can contribute to the creation of job opportunities and bioenergy value chains. Widespread household adoption of small-scale biogas digesters in Ethiopia has been hindered by numerous factors. A more formidable challenge to Ethiopia's efforts at modernizing its bioenergy potential and finding a competitive advantage is the lack of financial, infrastructural, and technical capacity. The scarcity of economic resources, particularly land for biofuel production, causes change in shadow prices, which affect relative prices and factor costs that could impinge on the livelihoods of the poor.

3.7.2.3. Social aspects

In assessing the sustainability of biofuels, social and economic dimensions have many overlapping facets. Social perspectives on bioenergy encompass such considerations as 'social and gender equity, participation, and equal rights,' which form the core of sustainable development (Jabareen, 2008). Rural Ethiopian society engages in traditional activities like farming and livestock production, which are directly linked to the availability of natural resources like water, grazing land, and forests. Hence, social sustainability implies modified or improved rights of indigenous communities over the use of natural resources and inclusion of the poor and disadvantaged in the development of bioenergy value chains. The welfare consequences, labour rights, and labour safety standards of large-scale biofuel activities are important social concerns. Important social issues include "labour conditions for workers engaged in the bioenergy industry and impacts on local communities of the bioenergy trade" (McCormick and Willquist, 2013). The ancillary benefits and risk factors need to be taken into account to assess the sustainability of biofuel projects and their effects on rural development. The degree of sustainability also relates to the potential for rural development, poverty reduction, and inclusive 'pro-poor' growth (FAO, 2013), which are also elements of economic factors. In contrast, the modern biomass use for the generation of clean energy is likely to reduce gender inequities inherent in traditional biomass energy use by reducing the burden of fuelwood collection and the health risks of IAP on women.

3.7.2.4. Environmental impact

Biofuels have both advantages and disadvantages with regard to environmental and natural resource sustainability. Concerns about large–scale biofuel activities include: land grabbing, land–use change (LUC), deforestation, and biodiversity loss (von Braun, 2008; FAO, 2013). These factors can either directly or indirectly affect not only the availability of natural resources, but also the welfare of local communities. In contrast, biofuel use is considered an instrumental measure for reducing GHG emissions from fossil fuels. In most cases biofuel investment projects are located on major rivers. Recent trends of drought patterns and climatic change have made water scarcity increasingly critical. The scarcity of critical resources like water and grazing land has already fuelled social conflicts between communities, tribes, regions, and nations in East Africa. A study of one of Ethiopia's national parks found that conflicts among different tribes surrounding the park were due to shortages of grazing land and access to park land (Kelboro, 2013). Competition between biofuel production and local needs for water and grazing land are expected to worsen the pressure that leads to such conflicts.

The potential environmental risks of large-scale biofuel production include: deforestation, soil mining, and water logging on land used for agricultural and forestry activities (Zeller and Grass, 2007). Deforestation and associated LUC induced by large-scale biofuel development also threatens biodiversity, ecotourism, and the value of affected habitat for wildlife. The net effects of biofuel development on biodiversity are not clear, due in part because environmental impacts depend on what type of biofuel is being produced and land use history. Small-scale private or communal afforestation and reforestation efforts, however, often improve local biodiversity and environmental conditions except when they involve large monocultures of eucalyptus or other species that have limited value to local wildlife. Biofuels can contribute enormously to energy security, environmental protection, and climate change mitigation efforts. Emissions arise from agricultural practices such as the use of agrochemicals and the harvest, deforestation, conversion, distribution, and fossil fuel use related to agricultural production (FAO, 2013). This means that biofuels can be both a solution for GHG emissions reduction as well as a cause of emissions. In general, the overall impacts of biofuel development on the environment are determined by the net impacts on biodiversity, GHG emissions, deforestation, land and water scarcity, and related issues. The net effects can be evaluated using a life cycle emissions assessment that takes into account emissions at all stages of production, processing, transportation, and consumption, as well as the GHG emissions reductions due to substitution of biofuels for fossil fuels.

3.7.2.5. Role of technological innovation and efficiency

The concept of innovation is frequently used in managerial, energy, and industrial economics to refer to creating value through new products or services. Efficiency is the creation of value through reducing cost or waste along production processes. The different technological pathways for converting biomass to energy have distinct implications for resource use efficiency. For instance, “generating electricity through the combustion of pure biomass is only approximately 30–35% efficient, while the combustion of the same material to produce heat is usually more than 85% efficient” (EEA, 2013). The most effective and safest use of biomass for modern energy generation is through the application of technical innovations that maximize the benefits and reduce risks, thus contributing to the triple sustainability indicators (economic, social, and environmental) as discussed above. In general, “using bioenergy for heat and power is a considerably more efficient way of reducing greenhouse gas emissions, compared to using bioenergy for transportation fuel” (EEA, 2013). The generation of different products along biomass energy value chains would improve overall efficiency. Technology will continue to play a major role in biofuel development by increasing production yields and the ability to convert energy crops and waste into biofuels (FAO, 2013). Innovation also improves the productivity and efficiency of resource use, agricultural productivity, and mitigates fuel-food trade-offs.

In developing countries energy technology is underdeveloped and characterized by lower efficiency or higher energy loss in the production, distribution, transmission, and consumption of energy. Building technological capability requires R&D, which in turn requires political commitment on the part of governments to invest in human capital formation and technical expertise. Continued R&D in biofuel has resulted in successive technological breakthroughs referred to as first, second, third, and fourth generation biofuels respectively. For instance, third generation microalgae emerged as promising option as it relieves pressure on food production, but many issues are under scrutiny such as its economic and technical viability (Demirbas, 2010). Value chains that integrate feedstock production, processing, and conversion to usable forms of energy enhance the opportunities for innovation and efficiency improvement, and hence the overall sustainability of the chain. Enhancing biomass use efficiency along all the stages of value chain to reduce waste and promote efficient and productive use of resources remain critical for improving the economic competitiveness of bioenergy.

International trade can create mutually beneficial outcomes by facilitating the flow of innovation, technology, food, energy, and capital that can facilitate sustainable bioenergy development. For instance, McCormick and Willquist (2013) stated that "increased trade is expected to drive the development and deployment of new and innovative technologies, particularly advanced biofuels for transport, there remain strong concerns that unregulated trade will not maximize the positive contributions of biofuels or minimize the risks." That report emphasized that Ethiopia's biomass resource potential, the availability of arable land, and government commitment are expected to drive the country's future international bioenergy trade opportunities. Minimizing the negative social and environmental consequences, and creating conducive institutions, will depend on the efforts of individual countries.

3.8. Review of the energy sector model

There is a diversity of methodological tools for energy sector models. Modelling exercises often involve complex interrelated optimization problems. To date energy sector models have not been fully explored for Ethiopia and Sub-Saharan African countries. With a rapidly growing economy, vast availability of renewable energy resources, and considerable economic and environmental pressures behind the need for energy security; studying the aggregate patterns of energy demand and supply, energy resource optimization, and possible technological options can provide invaluable insight for future energy policy development and planning.

In energy modelling literature features two basic modelling approaches: top–down (TD) and bottom–up (BU). Models are intended to examine the interactions within energy systems and national economies (Hourcade et al., 2006). Böhringer and Rutherford (2009) used the TD and BU approaches to represent aggregate and disaggregated energy models respectively. The TD approach has been applied in empirical models for the analysis of 'aggregated macroeconomic energy-environmental interrelationships' at national, regional, and global scales. In contrast, the BU approach has been used for specific 'disaggregated technical' issues and 'sectoral components' using more detailed information on energy generation technologies, and is often described as a 'technology-oriented' or 'energy modelling' approach. The BU approach is also referred to as the 'engineering model,' while TD is synonymous with 'economy model.' Both TD and BU energy modelling approaches have their own strengths and weaknesses that can result in divergent outcomes that are summarized in Table 3.4.

Table 3.4. Strengths and weaknesses of top-down and bottom-up modelling approaches

DESCRIPTION	STRENGTHS	WEAKNESSES	MODEL TECHNIQUE	EXAMPLES
		TOP-DOWN		
▪ Economy-wide models ▪ Aggregate model ▪ Economy-oriented approach ▪ Broader economic framework ▪ Standard finance dominated macro economics	▪ Explicit representation of the main economic factors ▪ Macroeconomic realism ▪ Comprehensive macroeconomic representation ▪ Captures market interactions and inefficiencies	▪ Higher costs ▪ Lack of detailed information on technological change ▪ Overcomes some physical barriers such as physical energy conservation ▪ Does not differentiate technology stocks from overall invested capital	▪ Computable General Equilibrium (CGE) model ▪ Long-term macroeconomic growth models (time series econometrics) ▪ Energy flow and demand in monetary units	CGE, GEM System dynamics, Time series-econometrics, Input-output analysis
		BOTTOM-UP		
➢ Energy system models ➢ Disaggregate model ➢ Technology–oriented approach ➢ Engineering model	➢ Low cost ➢ Easy to solve ➢ Detailed technological choices ➢ Technologically explicit	➢ Fail to represent market complexity ➢ Fail to incorporate key economy components such as labour, investment, capital, and consumption ➢ Neglect economy wide energy interactions ➢ Fail to represent macroeconomic adjustments ➢ Assume perfect foresight ➢ Restricted applicability to integral equilibrium	➢ Linear mathematical programming problems (LPP) ➢ Least-cost optimization of energy system activities ➢ Partial equilibrium representations of energy sector ➢ Energy flow and demand in material units ➢ Simulation models ➢ Multi-agent based model	➢ MARKAL ➢ MARKAL–MACRO ➢ MERG ➢ ETA ➢ TIMES ➢ MARKAL–ETL ➢ MARKAL–ED ➢ MARKAL Stochastic ➢ SOCIAL–MARKAL ➢ MESSAGE ➢ MESSAGE–MACRO ➢ ENEPEP/BALANCE ➢ POLES ➢ CIMS ➢ NEMS ➢ EFOM ➢ ICCMILP ➢ IKARUS ➢ BESOM ➢ LEAP ➢ Power–ACE

Note: See model acronym explanations in footnote[6]

3.8.1. Top-down energy models

In general there are four major families of TD energy models. The first TD model family includes econometric models that are 'time-series' or 'cross-country' in nature and are used to analyse long-term relationships among economic growth, energy markets, and related factors. For instance, Costantini and Martin (2009) applied a vector error correction model to examine the causality between energy consumption and economic growth. Second family TD models include 'computable general equilibrium' (CGE) models. Third family models include 'system dynamics models' (SDM) that capture complicated feedback loop effects from economic, market, and price factors from demand and supply perspectives, and deregulation of the electricity market (Teufel et al., 2013). The fourth family of TD models includes input–output models that are used to describe interactions among different economic sectors in terms of added value, and input and output coefficients that use empirical data on aggregate production, investment, GDP, etc. A recent study in Suzhou, China implemented a model that was "a hybrid physical input-output model for energy analysis (HPIOMEA)" that claimed to be better than current input-output models that "calculates energy resources in both energetic and mass units and air pollutants in mass units simultaneously and to illustrate the direct and accumulative effects of energy and air pollutants" (Liang et al., 2013).

TD models adopt an "economy-wide perspective that takes into account initial market distortions, pecuniary spill-overs, and income effects for various economic agents such as households or governments" (Böhringer and Rutherford, 2008). In these models technological change is described inexplicitly by the 'elasticity of substitution' (ESUB). The CGE model is popular as a result of its 'micro-foundations,' whereby households respond to price changes and are assumed to maximize utility, while firms are assumed to maximize profit and shift output in response to market signals (Wing, 2008). The CGE model was extensively applied to study energy and climate variability on the energy intensive economies of industrialized countries (Schumacher and Sands, 2006). Schumacher and Sands (2006) noted that for energy intensive industries in Germany, a TD economic model based on CGE is more realistic than alternative models. They integrated technological aspects of energy production using the 'constant elasticity of substitution' (CES) functional form to investigate the responses of the iron and steel industry to a set of CO_2 price scenarios. CGE has also been used to study emissions reduction and the impact of a carbon tax on the Australian economy and found that the greatest burden of the carbon tax fell on low-income households (Siriwardana et al., 2011).

3.8.2. Bottom-up energy models

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[6] EFOM = Energy Flow Optimization Model, LEAP = Long-range Energy Alternatives Planning system, NEMS = National Energy Modeling System, TIMES = The Integrated MARKAL-EFOM System, POLES = Prospective Outlook on Long-term Energy Systems, PRIMES = Partial Equilibrium Model for the European Energy System, ETA = Energy Technology Assessment, NAMES = National Energy Modeling System, MARKEL-ETL = MARKAL-Endogenous Technology Learning, MARKAL-ED = MARKAL Elastic Demand, LEAP = Long-range Energy Alternative Program, CIMS = Canadian Integrated Modeling System

BU energy models have been extensively applied for empirical analyses. BU models can be broadly classified into three major groups: optimization models, simulation models, and multi-agent models. Long-term energy sector planning has been articulated in numerous ways. The most widely implemented BU optimization model is the Market Allocation (MARKAL) model developed in the 1970s at the Brookhaven National Lab for the United States Department of Energy (DOE) and the IEA, and later introduced into energy economics by the IEA's MARKAL code (Fisherborne et al., 1982). The model employs a 'perfect foresight optimization approach' (Loulou et al., 2004). The MARKAL model is extensively used to study inter-linkages among energy, environmental, and economic systems based on a "multi-period linear programming approach and detailed information on technical aspects, emissions, and cost minimization" (Mondal, 2010).

A major drawback of the MARKAL model stems from the underlying assumption of 'perfect foresight' over the horizon of the plan period, which leads to 'optimistic solutions' as it is based on perfect knowledge of firms, consumers, current and future energy prices, and technological changes (Greening and Battaille, 2009). MARKAL models and other BU models are often constructed on the basis of exogenously defined key macro-economic variables including the responsiveness of different economic sectors' demand for energy services to shifts in market signals such as change in prices and drivers of demand like population, GDP, or income growth. It has not been possible to overcome some of the inherent flaws of these models.

Analysts have proposed many other BU energy models such as a hybrid 'inexact, chance-constrained, mixed-integer linear programming' (ICCMILP) (Liu et al., 2000), MARKAL-MACRO (Hamilton et al., 1992; Goldstein, 1995), MARKAL-MACRO-MICRO and MARKAL-ELASTIC DEMAND (MARKAL-ED) (Loulous and Lavigne, 1996). Other extended models include MESSAGE (Messner et al., 2000; Keppo and Strubegger, 2010), SOCIO-MARKAL (Nguene et al., 2011), "an optimization model for energy planning with inoperability constraints that was based on a source-sink framework for energy planning applications" (Tan, 2011), an "optimal combination of energy resources, technology, and investment at minimum economic cost on multiple scales using the BESOM" (Cai et al., 2007), and the IKARUS BU time-step model (Martinsen et al., 2007). Martinsen et al. (2007) used IKARUS, a dynamic time-step linear optimization model, to examine how energy price trends affect the development of Germany's energy system, the corresponding CO_2 emissions, and costs based on various price shock scenarios. Wallace and Flaten (2003) developed a "stochastic energy model to account for energy investment risks and uncertainty stemming from the unpredictability of energy demand and/or prices, and resource availability."

3.8.3. Hybrid energy models

These models have been proposed in an attempt to capitalize on the strengths and address the weaknesses of the two major modelling approaches through methods such as linking, coupling, integrating, or reconciling the technological explicitness of BU models and the economy-wide aspect of TD models. This would help researchers exploit the benefits of both approaches while minimizing their respective limitations (Graham, 1997; Labandeira et al., 2009). In general, three major types of hybrid TD-BU model are identifiable from the literature: (i) soft-link models; (ii) hard-link models; and (iii) the Mixed Complementarity Problem (MCP) format models to join the two models into a single integrated model (Böhringer and Rutherford, 2008). Since hybrid models integrate 'technological explicitness' and 'microeconomic realism' with 'macroeconomic completeness' to capture economy-wide, price-based policies within technology focused policy frameworks, they have more realistic performance than traditional TD models and better economic parameters than BU models (Jaccard et al., 2002). In hybrid frameworks the TD-BU models complement each other and enable analysts to mitigate constraints and build a model where aspects of both 'macro realism' and 'technological explicitness' are better represented.

Soft-link and hard-link hybrid energy models: Schmid et al. (2012) developed a hard-link hybrid energy model for Germany known as REMIND-D (Refined Model of Investment and Technological Development-Deutschland). Energy sector modellers have also found drawbacks of these hybrid energy modelling approaches. Soft-link models have two potential problems. First, the combination of the two models (TD and BU) can fail to achieve overall consistency (Hofman and Jorgenson, 1976; Jacoby and Schäfer, 2006). Second, the two approaches only complement one another when one of the two approaches is utilized in a reduced form, thereby compromising 'structural explicitness' (Messner and Schrattenholzer, 2000; Bosetti et al., 2006; Manne and Richels, 2006; Strachan and Kannan, 2008). Hard-link hybrid models integrate a distinct set of energy generation technologies into a TD model (Böhringer, 1998; Wing, 2006; Böhringer and Rutherford, 2008), in which case "the representation of technological detail significantly increases the dimensionality of the model, thus severely constraining large–scale applications" (Lanz and Rausch, 2011).

Mixed complementary problem hybrid models: Another hybrid TD-BU modelling approach is called the mixed complementary problem (MCP) approach. This approach is based on the 'decomposition algorithm' of Böhringer and Rutherford (2009), which employs an iterative solution procedure to solve the TD and BU model components consistently (Böhringer and Rutherford, 2009; Lanz and Rausch, 2011). Böhringer and Rutherford (2008) applied the MCP approach to investigate the relationship among economic, energy, and environmental factors in order to better understand the ability of renewable energy policies to mitigate climate change. MCP was intended to address the problem of TD and BU hybridization through "an explicit representation of weak inequalities and complementarity between decision variables and functional relationships to exploit the advantages of each model type in a single mathematical format" (Böhringer and Rutherford, 2008).

TD and BU models are essentially flip sides of the same coin. The former maximizes objective function (i.e. profit or utility subject to constraints), while the latter minimizes the cost of energy generation subject to constraints. This situation creates complementarity between the two models (Jacobsen, 1998). In the energy model, the hybrid approaches were found to increase the reliability of TD models as the substitution patterns in energy conversion are based on the real 'technology explicitness' instead of presumed 'restrictive functional forms' (Böhringer, 1998; Labandeira et al., 2009).

3.9. Model choice and description

The hybrid approach would be the best energy modelling option overall, however, these require much more detailed data than were available and are beyond the scope of what could be accomplished. Also, these models are more appropriate for energy-intensive, developed countries than for developing countries like Ethiopia where many of the technologies are underdeveloped and technical problems are more relevant. This makes it imperative to study details of the energy sector plan and future policy goals, which are more technical issues that can be addressed more adequately by the BU modelling approach.

Model choice was primarily guided by research objectives. The primary challenge to the development of Ethiopia's energy sector is the sustainable exploitation of renewable energy resources to enable competitive advantages as well as energy security. A dynamic linear programme for identifying a least-cost power generation strategy is better suited to address this challenge. The country's potential for clean renewable energy generation could be realized through optimal energy mix diversification. This could contribute to a competitive advantage in the export of renewable energy sourced power. The application of renewable energy technology could also help address energy access problems in off-grid areas.

The objective of the model was to minimise the expected future costs of energy production over a simulated time horizon. The optimization problem was defined in terms of determining plant capacities and energy outputs for the six major energy resources: fossil thermal,[7] biomass, hydroelectric, wind, solar, and geothermal, such that the total cost of energy provision throughout the year is minimised. The model outputs are projections of the total annual energy production (in GWh), overall capacity (in MW), and quantity (in millions of tonnes) of solid biomass energy each year.

The model was created using General Algebraic Modelling Systems (GAMS) software.[8] The model was based on a time-dependent dynamic linear programing model. Chang and Hin Tay (2006) used a similar model to examine the effects of efficiency and deregulation on costs in the 'New Electricity Market of Singapore.' The original model design was modified to evaluate the effects of different sources of uncertainty, including: changes over time in the rate of technological innovation, efficiency, and land rental costs, and the effects of climatic change or drought on the cost of energy production required to satisfy projected demand over the simulation period and diversification of the energy sector.

Model iterations included a long-term simulation of the 2010-2110 period that was divided into twenty 5-year periods. The base year and simulation periods were aligned with the Ethiopian federal government's 5-year economic growth plans (GTPs) beginning at the current (2010-2015) gross domestic product (GDP). Each 5-year period was subdivided into fiscal years with distinct periods reflecting daily and weekly patterns of 'peak' and 'off-peak' electricity demand.

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[7] Fossil thermal refers to power generation from fossil fuels such as diesel as opposed to geothermal.

[8] From GAMS Software, available at www.gams.com.

The objective function, Θ, was stated as the total sum of three costs discounted over the entire simulation period (2010-2110), including: (i) the total operating and management costs of all plants and energy sources over the time period $(t)(c_t^o)$, (ii) the total system capital costs of all power plants and energy sources over the time period $(t)(c_t^k)$, and (iii) the land rental costs for biomass feedstock production over the time period, $(t)(c_t^a)$. The mode equations are described in Box 3.1.

Box 3.1. Equations used in the Ethiopia energy sector model

$$\min_c \Theta = \sum_{1=1}^{T}[(1+\rho)^{-t}\,(c_t^o + c_t^k + c_t^a)] \tag{3.1}$$

Subject to:

$$\sum_{i=1}^{n} A^i(P_i) \geq (1+\tau)X_{td} \tag{3.2}$$

$$X_{td} < \sum_{i=1}^{n}\sum_{j=1}^{6} P_{ij} \tag{3.3}$$

$$X_{st} \leq \sum_{m=0}^{9} Q_{sm} \tag{3.4}$$

$$P_{ijtd} \leq A^i.Q_{ij} \tag{3.5}$$

$$\sum_{i=1}^{6}\sum_{j=1}^{J} Q_{ij} \leq S.X_{td} \tag{3.6}$$

$$\sum_{j=1}^{n} Q_{ij} \leq Q_{MAX}^{i} \tag{3.7}$$

$$0 \leq Q_{ijt} \leq Q_{MAX}^{ij} \tag{3.8}$$

$$c_t^k \leq K_0\big(1+(\kappa-\pi)\big)^t \tag{3.9}$$

$$\sum_{t=1}^{T}\sum_{m=1}^{9}\{a_{bmt}+a_{smt}\} \leq \sum_{m=1}^{9}\{E_m + F_m\} \tag{3.10}$$

$$\sum_{m=1}^{9} a_{sm} \leq \delta.E_m + \rho.F_m;\ \&\sum_{m=1}^{9} a_{bm} \leq (1-\delta).E_m + (1-\rho).F_m \tag{3.11}$$

The term ρ is the discount rate, which reflects the weighted average cost of capital (WACC). The mean national interest rate (i) from the National Bank of Ethiopia (NBE) for the last decade (2001–2010) of 7.87% (NBE, 2011) was used to compute discount rates in the model as ($\rho = \frac{i}{(1+i)}$). The operation and management costs are the total annual expenditures of all power plants and energy sources over the specified period. At time period (t) total costs were estimated by multiplying annual costs per MW of energy by the amount of energy produced (in MW) each year. Load duration was broken down into d discrete blocks. The parameter ($\emptyset_{\boldsymbol{d}}$) is the amount of time that each demand block lasts over the course of each year (in hours). Only two demand blocks were used for simplicity's sake: 'peak' and 'off-peak' (the mean of 'high,' 'medium,' and 'low' blocks). This was not expected to cause significant bias because Ethiopia faces acute electricity shortages during peak demand hours. The variable P_{ij} is the decision variable (in MW per year) of energy source (i) corresponding to plant (j) in time period (t) during load block ($\emptyset_{\boldsymbol{d}}$). The cost per MW, ($o_{ij}$), is assumed to be fixed for each energy source or does not vary by plant of the given energy source and block (d). It was assumed that this cost would vary over time due to efficiency improvements or 'the learning effect,' which was examined using scenarios with distinct efficiency improvement rates. The term c_t^o was obtained by adding o_{ijt} of all operating plants, energy sources, and load blocks, which was determined as:

$$c_t^o = \sum_{i=1}^{n}\sum_{j=1}^{J}\sum_{t=1}^{T} o_{ijt} \,.\, P_{ijt} \,.\, \emptyset_{\boldsymbol{d}} \qquad (3.12)$$

Another cost component is the total system capital cost, c_t^k, which is the total capital expenditure on capacity (Q_{ijt}). The per unit capital cost (k_{ijt}) is in MW per year. In the model a capital cost constraint was imposed based on Eq. (3.13) in order to constrain capital investment to the growth in base capital investment (K_0). Thus c_t^k is the sum total of capital investment during period t, specified as:

$$c_t^k = \sum_{i=1}^{n}\sum_{j=1}^{J}\sum_{t=1}^{T} k_{ijt} \,.\, Q_{ijt} \qquad (3.13)$$

The third cost component is land rental opportunity cost, specified as the total land rental opportunity costs of producing biomass feedstock for generating electrical energy and solid biomass for traditional use. The term r_{bmv} represents the per unit land opportunity costs of biomass electrical energy in per MW each year and r_{smv} is the per unit land opportunity cost of solid biomass per million tonnes each year. Thus the total land opportunity cost (c_t^a) is the sum of the two costs depending on which purpose land is allocated to, specified as:

$$c_t^a = \sum_{m=1}^{9} r_{bmt} \cdot Q_{bmt} + \sum_{m=1}^{9} r_{smt} \cdot Q_{smt} \tag{3.14}$$

The detailed model sets, variables, and parameters are described in Box 3.2. The model is based on constraints regarding output, energy resource availability, the area occupied by different land cover types such as forest and marginal arable land available for afforestation or reforestation efforts, energy demand stability, energy system reliability, and capital resource investment availability. Complete descriptions of the model constraints are presented in Annex 3.1.

Box 3.2. Variables and parameters used in the Ethiopia energy sector model

Sets

T	set of years from 2010 to 2110
t	time in individual years ($t = 1,2,3, \dots t$)
i	energy sources ($i = 1, 2, \dots, 6,$), i.e. hydroelectric, fossil thermal, biomass, geothermal, wind, solar
j	plant type ($j = 1, 2, 3, \dots$ J)
m	region (m = 1, 2, 3,…9)

Variables

Θ	total discounted minimized cost (US$)
c_t^o	total operating and management costs at time *t* (US$)
c_t^k	total capital costs at time *t* (US$)
c_t^a	total land opportunity costs at time *t* (US$)
P_{ij}	energy output of the individual plant j of energy source i at time period *t* during load block d (MW)
Q_{ij}	capacity of the individual plant j of energy source i
Q_{bm}	biomass electricity capacity of region m
Q_{sm}	solid biomass capacity of region m
o_{ijt}	the cost per output of energy source (i) of the plant (j), which does not vary by load block d (US$/MW/year).
k_{ijt}	capital costs per MW of capacity (US$/MW)
r_{bm}	land costs per MW of capacity for biomass electricity (US$/MW)
r_{sm}	land costs per tonne of capacity for solid biomass energy (US$/tonne)
a_{bm}	land area (in hectares) used to supply biomass feedstock for electricity in region m
a_{sm}	land area (in hectares) used for supplying solid biomass energy in region m

Parameters

i	interest rate
ρ	discount rate
K_0	capital investment in energy production in base year (US$/year)
κ	capital investment growth rate per year
π	inflation rate per year
δ	proportion of existing forest cover used for providing solid biomass
ρ	proportion of prospective forest cover used for providing biomass feedstock for

	electricity generation
d	blocks of electricity demand
$\emptyset_d$	duration of each electricity demand block in hours per year
τ	peak reserve requirement ratio
A^i	availability rate
g	electricity demand growth rate per year
u	solid biomass demand growth rate per year
X_{td}	mean demand of each load block (MW)
X_s	solid biomass energy demand (millions of tonnes per year)
F_m	marginal land available for prospective afforestation/reforestation efforts
E_m	existing forest cover area
Q^i_{MAX}	maximum theoretical potential of energy resource (i) in the country
Q^{ij}_{MAX}	plant j's maximum capacity for energy source (i)

3.10. Data and parameters used in the Ethiopia energy sector model

The data and parameters used in this effort were combined from different sources produced by EEPCO, data on the national energy supply, and other documents such as reports from the scaling-up renewable energy programme of the MoWE investment plan, the Central Statistical Authority (CSA), studies on electricity generation in Ethiopia, and selected case studies. Table 3.5 shows the main data sources used for this research. More detailed information is presented in Table A 3.8 and Table A 3.9. Box 3.3 shows the main parameters used in the model.

The main parameters used in the baseline scenario of the model are presented in Box 3.3. The country's current total annual hydroelectric capacity of about 45 GW, wind capacity of about 10 GW, and geothermal capacity of about 5 GW were considered in the model. The potential solar energy capacity was assumed to be non-binding in the model.

The main challenge to biomass energy production was considered to be land constraints. Land tenure rights have also become a major political, economic, and social issue in Ethiopia. This is because of poorly defined property rights, particularly for the ownership of small properties. Rapid population growth has contributed to land scarcity. Large-scale land acquisitions by corporations (in many cases considered 'land grabbing') are also a problem that has contributed to land tenure security concerns. Furthermore, inter-regional mobility within Ethiopia is a potential cause of conflict between indigenous groups and migrants from other regions. All nine regions of the country were included in the analyses.

Biomass energy use was considered in two forms: solid biomass for traditional purposes and for electricity generation. Biomass traditional solid biomass capacity and electrical energy were estimated based on land-use projections using Eq. (3.11)[9]. Biomass was sourced from about 3.34 million hectares of existing forest cover (FAO, 2010; WBISPP, 2004) and 2.63 million hectares of marginal land (fallow crop and grazing land) assumed to be afforested or reforested based on the Ethiopian Agricultural Sample Enumeration conducted in 2010 and 2011 (CSA ,2012). Figure 3.9 shows Ethiopia's forest cover in 2009.

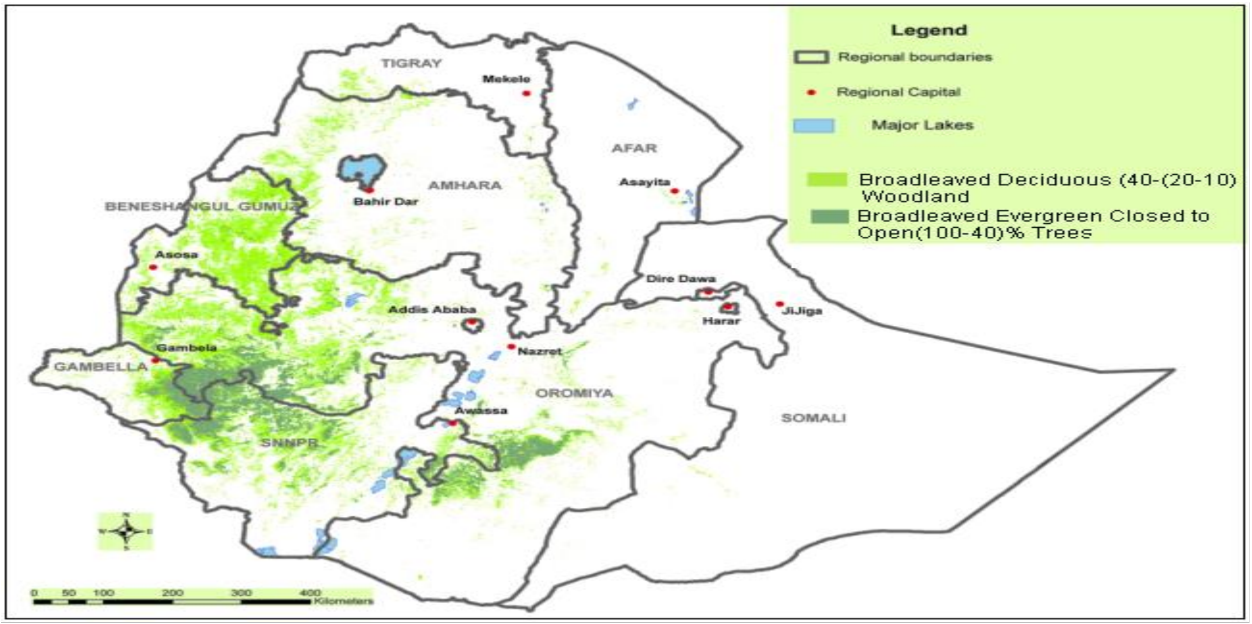

Figure 3.9. Ethiopia forest and woodland cover in 2009 by administrative regions

Source: Winberg (2010)

Recently Ethiopia has implemented large-scale efforts to establish tree plantations as well as reforestation and rehabilitation efforts on degraded marginal lands including afforestation projects on river floodplains in order to combat the effects of climate change.[10] The model only considered the area designated as forest cover to estimate biomass production to account for other competing demands for forest products[11]. Though the model only considered forest cover, it is important to consider the potential opportunity of using other forms of vegetation for biomass energy[12]. Biomass yields per hectare were estimated from sustainable annual yield (Guta, 2012b) and forest cover (FAO, 2010) data[13]. The conversion factor of biomass to electricity was based on estimates by the European Commission (2004) and certain

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[9] In the model parameters of forest use (δ and ρ) were such that 82% was used for the solid biomass energy and 18% for electricity.

[10] Available at http://www.independent.co.uk/environment/ethiopias-forest-cover-triples-ministry-2029508.html, accessed on 9/07/2014.

[11] Timber, non-timber resources, and biodiversity conservation.

[12] Bushes and invasive plant species in arid and semi-arid lowlands, as well as woodlands other than forest cover.

[13] Mean annual yield at the national scale is about 8.5 t/ha/year, which varied within a range of 6–10 *t* across regions.

assumptions[14]. Land rental costs for each region were obtained from the Ethiopian Investment Authority (EIA, 2011).

The trend in historical Ethiopian electricity generation data from 1961 to 2011 is presented in Table A 3.1. There was tremendous growth in power generation capacity over the last decade (2001–2010), from 479 MW to about 2,009 MW annually. EEPCO reported that in 2011 the Ethiopian power system was composed of 11 hydroelectric (ICS) power plants with a total annual capacity of 1,843 MW, 15 diesel thermal power plants with a total annual capacity of 159 MW, and one geothermal power plant with an annual capacity of 7.3 MW, which together produced up to a total of 2,009 MW. The existing and expected hydroelectric power generation costs and capacities are listed in Table A 3.7. There are significant differences in capital costs, ranging US$ 909-2,760/kW. Costs drop significantly with increasing generation capacity of the power plants, although the relationship is not monotonic. The federal government's plan to expand hydroelectric capacity begins with the Gilgel Gibe III plant, which is expected to be completed by 2014, while the proposed GERD facility will have an annual capacity of 6,000 MW.

Capital costs and the capacity of selected Ethiopian hydroelectric plants are described in Table A 3.6. The capital cost per unit (MW) varies significantly with capacity. The technical and cost coefficients of 28 hydroelectric plants (with a combined maximum annual generating capacity of 26,922 MW) are described in Table A 3.5. Based on EEPCO research the technical cost coefficients of 28 hydroelectric power plants with a combined maximum annual generating capacity of 26,922 MW were included in the model. For the remaining hydroelectric plants the mean capital cost (US$ 1.97/MW) and plant load factor (57.5%) were used.

Recently the solar industry has been undergoing significant innovation in terms of efficiency improvement. Solar efficiency has increased from below 30% to about 45% and the current target of solar PV manufacturers is to achieve 50% efficiency. This is expected to drive the cost of solar power down in the future, increasing the potential for solar power generation in the country. Facilities for intermittent energy resources such as solar and wind were assumed to have lower plant factors of 30% and 40% respectively. In the case of biomass electricity power a 68% efficiency rate was considered following Böll (2010).

The amount of financial resources available for energy development is subject to a capital investment cost constraint calculated using Eq. (3.9). The terms K_0 and κ were computed using information from EEPCO on investment cost breakdowns by generation, transmission, and distribution costs, and also from the Universal Energy Access fund for rural electrification for the 2005-2010 period. The respective exchange rate was used for each year and the annual

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[14] One tonne of forest biomass equals 100 kWh of electricity and 50 kWh of heat (EC 2004). It was assumed that 1 *t* of biomass feedstock would provide 10% of power operation time ([0.1*365*24] = 876 hours of service), therefore 1 *t* of feedstock generates about 171 MW of power.

growth rate was 16%. The mean inflation rate for Ethiopia over the period from 1982 to 2010 was 7.5% (World Bank, 2013c). Therefore, inflation was set at the adjusted annual capital growth rate of 8.5%.

Table 3.5. Main data sources used to establish Ethiopia energy sector model parameters

Data type	Amount	Units	Sources
Forest cover of all nine regions of Ethiopia in 2005	Refer to Table A 3.9	Hectares	FRA, FAO (2010) reclassification, calibration, and linear extrapolation of data from the Woody Biomass Inventory and Strategic Planning Project (WBISPP, 2004)
Marginal fallow and grazing land	Refer to Table A 3.9	Hectares	The Ethiopian Agricultural Sample Enumeration (EASE) was conducted in 2010 and 2011, CSA (2012)
Solar capital cost	4.9	US$ millions/MW	Mean value computed from IEA/NEA (2010) for concentrated solar power
Geothermal capital cost	3.8	US$ millions/MW	MoWE (2012)
Hydroelectric capital cost	1.97	US$ millions/MW	Mean value computed from 28 hydroelectric power plants with a combined maximum generating capacity of 26,922 MW (see Table A 3.6);
Wind capital cost	2.3	US$ millions/MW	Adama Wind Park, MoWE (2012)
Diesel thermal capital cost	0.8	US$ millions/MW	Estimate
Biomass power capital cost	2.4	US$ millions/MW	Technical cost of LFG power generation under construction in Addis Ababa, and NREL (2012)
Land rental cost	Table A 3.9	US$ millions/ha converted to per energy equivalent	Extracted from (EIA, 2010) and adjusted for each region’s proximity to the capital
Biomass yield per hectare	Table A 3.9	Millions of tonnes per hectare	Computed from sustainable biomass of each region as in Guta (2012b), at about 9.5 t/ha per year for Oromia
Biomass conversion to power	171	MW/millions of tonnes	EC (2004) and assumptions based on information described in Table A 3.9
Capital investment cost	628	US$ millions per year	In 2010 from EEPCO (2011)
Capital investment cost growth rate	8.50%		Mean of 2005–2010 (EEPCO, 2011) adjusted for inflation
Initial hydroelectric power capacity	1,843	MW	EEPCO (2011),
Initial fossil thermal installed capacity	159	MW	MoWE (2011)
Initial geothermal installed capacity	7.3	MW	MoWE (2012)
Solid biomass demand 2010	52	Millions of tonnes per year	MoWE (2011)
Power demand ICS or grid	856	MW	EEPCO (2011)
Power demand from SC	196	MW	EEPCO (2011)
Power exported to Djibouti 2010	60	MW	EEPCO (2011)

Note: See Table A 3.8 and Table A 3.9 for greater detail

Annual fuelwood and charcoal demand in the base year (2010) were estimated at 52 million tonnes and grew at mean annual rate of 2.46% over the decade 1999-2010 (MoWE 2010). It was assumed that a lower annual growth rate of 1.5% would reflect future demand (2010-2045) based on expected population growth rate decline, expected efficiency improvements (e.g. broader household use of improved fuelwood stoves), and substitution of more modern forms of energy for traditional solid biomass use. Over the long term (2045-2110) it was assumed that demand for solid biomass would remain constant because population growth is expected to stabilise.

Energy demand projections were based on the peak load duration and reserve requirements. The total annual load duration of 8,760 hours was divided into two blocks. Peaks occur on weekdays (8:00AM-12:00PM and 1:00PM-5:00PM) and for two hours on weekends, for a total of 2,640 hours per year. The remaining 6,120 hours per year were considered off-peak. The peak reserve requirement was assumed to be 5% of the peak demand. The mean electricity consumption growth rate over 2002-2011 was about 11% (EEPCO, 2011). However, the electricity demand growth rate may vary over the long term. Maximum annual demand growth rate was set at 9% and minimum was set at 6% for the 2010-2045 period and it was assumed that demand would grow at 2.5% annually from 2045 to 2110 due to the stabilisation of economic and population growth over the long term. The power demand projections were based on the base year power load reported by EEPCO. The ICS peak load was about 856 MW in 2010, with base and off-peak loads of about 648 MW and 468 MW respectively. Together with the SCS and power export the peak electricity demand was about 1,112 MW (EEPCO 2011). The peak, mean, and minimum loads in 2010 are depicted in Figure A 3.1.

The capital costs per MW (k_{ij}), the operation and management costs per MW per year (o_{ij}), and the availability rates for each energy source were estimated from the sources listed in Table A.3.9. The main limitation on estimating fossil thermal electricity production was the lack of disaggregated data on fuel type (diesel, coal, or coal and gas). The only information available is that in 2009-2010 Ethiopia used about 4,995 TJ of petroleum to generate electricity and had an installed fossil thermal power capacity of about 159 MW (MoWE, 2011). A conversion rate of 0.031 was used to convert Terajoules to megawatt equivalents. In 2010 the price of petroleum was US$ 0.78/litre (Figure A 3.2) and the fuel requirement for power generation was 265.5 litres/MWh (EEPCO, 2010), which were considered in the model. The operational life expectancy for biomass, solar, and wind power plants was assumed to be 25 years, whereas hydroelectric and geothermal plants were expected to operate for 50 and 30 years respectively.

Box 3. 3. Baseline scenario parameter values used in the Ethiopia energy sector model

i	7.87% interest rate (NBE, 2011)
K_0	US$ 628 million per year (EEPCO, 2011)
κ	16% per year (EEPCO, 2011)
π	7.5% (World Bank, 2013b)
δ	0.82
ρ	0.18
d	peak and off-peak loads
$\emptyset_d$	peak load of 2,640 hours per year and off-peak load of 6,120 hours per year

τ	0.05 of peak demand in each period to allow for any unexpected power shortfall
A^i	see Table A 3.9 for each energy source
g	high (0.09) and low (0.06) for 2010-2045, and 0.025 for the remainder of the simulation period (2045-2110)
u	0.015 for 2010-2045, and no growth for the remainder of the simulation period (2045-2110)
X_{td}	peak demand of 1,112 MW is the sum of interconnected systems, self-contained system (SCS) , and power export to Djibouti; off-peak demand of 648 MW (EEPCO, 2011)
X_s	52 million tonnes/year (MoWE, 2010)
F_m	2.63 million hectares by region (CSA, 2012)
E_m	3.34 million hectares of forest by region (FAO, 2010)

3.11. Description of alternative scenarios

The key assumptions of the baseline and alternative model scenarios are presented in Box 3.4. Two sets of scenarios were considered. The first set consists of different rates of cost reduction from learning and technological advances for solar, wind, biomass, and land rental change, as well as the shadow price of resource constraints. Newer energy technologies were expected to have greater learning and innovation rates than more mature (hydroelectric and geothermal) technologies (Winkler et al., 2009). Recent estimates of the impacts of technological and efficiency innovation on the cost of different types of renewable energy are summarised in Table 3.6.

Hydroelectric power is a commercially proven technology and is less likely to have as significant cost reductions in the short- to mid-term (IRENA, 2012b). "Technology is an important driver of energy development and technology costs change over time" (Winkler et al., 2009). It was assumed that technological progress and economies of scale will reduce capital costs. For instance, one study found three reasons for reductions in the cost of solar power: (i) increasing solar panel manufacturing capacity of China, (ii) technical innovations in hardware, and (iii) increased investment in solar power at the industrial level (Pillai and Cruz, 2013).

However, the rate of technical progress in renewable energies varies, and it is expected to be higher for solar and wind than geothermal and hydroelectric. The estimate of the rate of learning and technical growth in renewable energy differs from study to study. For solar PV the learning rate was estimated to be 17% over 1992-2000, for wind it was estimated at 10-12% over 1990-2000 (Papineau, 2006), and for small-scale biomass for electricity generation was estimated to be 17% over 2003-2025 (UNEP, 2006). It is assumed that newer technologies, renewable or otherwise, will have higher learning rates than more mature technologies (Winkler et al., 2009). Recent estimates of the impacts of technological innovation and efficiency on the cost of different types of renewable energy are presented in Table 3.6.

Table 3.6. Estimated declines in the cost of renewable energy options due to technological and efficiency innovations

Energy source	Rate of cost decline
Wind	15% over 2011-2020 or 28% over 2011-2040 (IRENA, 2012a)
Solar CSP	30% to 40% by 2020 (IEA, 2010), 10% for capital costs and 5% to 10% in O&M costs over 2011-2015 (IRENA, 2012b)
Biomass	Wood gasification for power generation should experience a capital cost reduction of 22% by 2020 (IRENA, 2012c)

Hydroelectric energy has a longevity advantage, but is highly susceptible to drought. Geothermal energy has high longevity, capacity, and stability unlike wind and solar energy resources, which are intermittent and/or seasonal and thus require storage facilities and related additional costs. In general, the cost reduction effect of technological innovation and efficiency may be lower in the short term as the country would need to import all associated hardware, but over the long term the country may be able to manufacture required hardware.

As discussed above, technical innovation, increased efficiency, and earning/adaptability effects result in decreasing renewable energy costs. There has been a substantial decline in the cost of solar energy hardware in recent years (Timilsina et al., 2012). This trend is expected to continue as many innovations are integrated into system processes and plant operations for wind and solar facilities. Although there is no certainty about the future advancement of technological innovation, the expected trend is reflected in declining power plant costs. Furthermore, cost reduction advantages depend on economies of scale, longevity, and capacity factors. Hydroelectric power has a longevity advantage, but is susceptible to drought. Geothermal power has potentially high capacity and stability unlike wind and solar, which are intermittent and/or seasonal and thus require storage facilities at additional cost. Jordan (2013) found that for each time the installed capacity of solar PV doubles, the module costs declines by 22% and that over the two previous years alone PV module costs had declined by estimated 60%.

However, in the case of Ethiopia the cost reduction effect may be lower over the short term as the country needs to import hardware, but over the long term the country may be able to manufacture some of the hardware. Hence, a scenario analysis was developed to examine the effects of technical progress, efficiency, and land opportunity cost. Scenario analyses also help control for uncertainties related to the cost coefficients of power resources. It has been observed that “many technologies exhibit an S-curve in their performance improvement over time” (Ayres, 1994; Schilling and Esmundo, 2009). This is attributed to slow improvement in the early stages of technology adoption because the fundamentals are poorly understood, but as experience leads to profounder understanding of the renewable technology, improvement accelerates and eventually reaches the greatest rate of improvement as the technology matures, enabling performance to improve more rapidly. At some point returns diminish as the technology reaches its inherent climax and the cost of each marginal improvement increases (Schilling and Esmundo, 2009).

The impact of technical innovation is reflected in reducing the per MW capital costs (k_{ij}), paving the way for increases in installed capacity (Q_{ij}), that in turn result in greater energy production (P_{ij}). Technical innovation also results in a decline in minimised total cost (Θ) because it is associated with a drop in capital cost (c_t^k). Improvements in efficiency, learning, or adaptability reduce costs (o_{ij}) and thus c_t^o, directly affecting energy production and ultimately overall discounted cost and installed capacity as plants are able to supply more energy. These also affect the shadow price of energy resources.

The second set of scenarios examined the impacts of climate change, which are expected to affect the national energy system through changes in water availability over the long term. Water shortages affect the volume of reservoirs and subsequently hydroelectric power generation capacity. Increased frequency and severity of drought as a result of climate change are expected to reduce water availability (A^i) by affecting the amount of energy produced (P_{ij}) and through impacts on c_t^o, that increase minimised total cost (Θ). This is because renewable energy resources with the potential to substitute hydroelectric energy are expensive. Funk and Marshal (2012) found that over the past decade (2000–2010), mean rainfall in most areas of Ethiopia fell below historic mean precipitation levels by a standard deviation of 0.40. Cheung et al. (2008) computed the standard deviations of precipitation change for 13 watersheds in Ethiopia and found a mean standard deviation of 0.11 over the last three decades. We considered different standard deviations of change to predict the impacts of climate change or drought on water availability and resulting hydroelectric energy production capacity and costs (Box 3.4).

Box 3.4. Scenarios in the Ethiopia energy sector model

Baseline

- No decrease in operating cost per MW/year
- No decrease in capital cost per MW
- Annual growth in land rental opportunity cost per MW = 5%
- Water availability = 0.90

Technological growth rate and efficiency (learning) effect and land rental change scenario

Low growth scenario:
- Annual decrease in operating costs per MW = 0.5%
- Annual decline in capital costs per MW by 1% for solar, and 0.5% for biomass and wind
- Annual growth rate in land rental opportunity costs = 3%

Intermediate growth scenario:
- Annual decrease in operating costs per MW = 1%
- Annual decline in capital costs per MW by 3% for solar, and 1% for biomass and wind
- Annual growth rate of land rental opportunity costs = 2%

Best case growth scenario:
- Annual decrease in operating costs per MW = 2%
- Annual decline in capital costs per MW by 6.5% for solar, and 3% for biomass and wind
- Annual growth rate of land rental opportunity costs = 1%

Drought scenarios

Drought scenario-1:

- Water availability variability based on a standard deviation of 0.11

Drought scenario-2:

- Water availability variability based on a standard deviation of 0.25

Drought scenario-3:

- Water availability variability based on a standard deviation of 0.40

The third alternative scenario examined the impact of electricity access interventions on Ethiopia's power generation expansion. The health impacts of IAP are a common concern in Ethiopia, where most rural households rely on traditional biomass stoves, which are inefficient and generate considerable amounts of smoke that contains soot and carbon monoxide. Ethiopian energy policy emphasizes fuel–switching from biomass to electricity (which is expected to liberate biomass feedstock for power generation). The contribution of different levels of increased electricity access intervention to reduced solid biomass consumption (X_{st}) and increased biomass electricity generation were examined. It was assumed that the policy interventions would reduce the proportion of forest cover used to supply solid biomass (a_{sm}) by shifting parameters (δ and ρ) and thus release increased forest area for supplying feedstock for biomass electricity generation (a_{bm}).

3.12. Model validation

Data on Ethiopian power consumption and solid biomass energy consumption from 2000-2010 were used to validate the model results. Data on peak demand and installed capacity were obtained from EEPCO (2011). Energy balance data were obtained from MoWE (2010b), which provides details about solid biomass energy consumption and electricity generation by resource for the 2000-2010 period. In 2000 the country's annual GDP growth rate was 6% and the annual population growth rate was about 2.7%. The annual installed capacity was 401 MW of ICS and 20 MW of SCS at that time. This included about 7.3 MW of geothermal. There was no clear distinction in the data on the proportion represented by fossil thermal, therefore it was assumed in the model that the SCS component was attributable to fossil thermal.

Energy demand reached a peak load of 328 MW for ICS and 13 MW for SCS. Data from MoWE described in Figure 3.6 indicate that the total solid woody biomass energy consumption (fuelwood and charcoal) was about 715,804 TJ or about 39 million tonnes in 2000. During the 2000-2010 period the country built four hydroelectric power plants; Gilgel Gibe I in 2004, Tekeze in 2009, and Beles and Gilgel Gibe II in 2010. For more information on investment costs and installed capacity of these power plants see Table A 3.5. These power plants were considered for validation of the model in addition to the 28 proposed hydroelectric projects. On the basis of population and economic growth rates, predicted demand for solid biomass and power grew annually at 2.7% and 9% respectively.

In order to assess the robustness of the model results a regression analysis proposed in the literature (Kleijnen, 1998; Börner, 2006) was applied. The regression equations for the installed capacity and power generated respectively were:

$$y_A - y_P = \gamma + \theta(y_A + y_P) + \varepsilon \tag{3.15}$$

$$z_A - z_P = \gamma + \theta(z_A + z_P) + \varepsilon \tag{3.16}$$

where z_A and z_P represent the actual and predicted shares of different energy sources of the total power generated, and y_A and y_P represent the actual and predicted shares of different sources in the total installed capacity, γ and θ are parameters, and ε is an error term. The model validation test requires detecting whether the model results are significant or not using an f-test. If the null hypothesis that $\gamma = 0$ and $\theta = 0$ is not rejected, then the model is considered robust.

A comparison of data to the model results for installed power capacity and generated power is presented in Table 3.7. In both cases the F-test results did not support rejecting the null hypothesis, even at a high level of significance, indicated that the model results were robust, at least over the short term. Compared to empirical data the predicted model results for installed capacity fell short by about 688 MW annually for hydroelectric power and by 137 MW for fossil thermal. In comparison to actual installed capacity, the total installed capacity shares of hydroelectric and geothermal were lower in the model predictions by 5.8% and 0.2% respectively relative to the empirical shares, which were accompanied by a 6.1% decline in fossil thermal power.

Annual power generation predicted by the model fell short of the actual generated amount by 397 GWh, which corresponded to 147 GWh of hydroelectric and 279 GWh of fossil thermal power. The predicted increase in geothermal power generation by 29 GWh annually was mainly due to more efficient capacity utilization. Compared to the actual power generation composition, the predicted shares of hydroelectric and geothermal were about 6% and 1% higher respectively. These were accompanied by a predicted decline in the share of fossil thermal of about 7% (Table 3.7).

There are numerous possible explanations for the divergence between the predicted values and the data. First, the initial conditions considered in the model were different from what actually occurred in Ethiopia. For instance, the mean annual GDP growth rate was about 8.6%, which was higher than 6% used in the model. Greater economic growth was likely accompanied by more demand for power.

Though there was a large difference between installed and predicted capacity, the difference in actual and predicted power generation was only 397 GWh per year. This explains part of the paradox the country is facing (i.e. despite increased power generation chronic power shortages remain a challenge). This may be attributable to the limited capacity of existing distribution and transmission infrastructure. If the installed power plants are not operating efficiently the economic loss on the investment of capital resources would be high. Power efficiency or loss in the distribution and transmission system causes an energy crisis. With increasing peak load demand and the country’s ambition to export power, however, the country should measures to correct such problems. Concurrently to diversifying its power generation mix the country should consider emphasizing reforming governance for the decentralization of power generation and distribution at the regional level as well as for small-scale schemes like off-grid community systems, and implement various other measures to develop relevant institutional capacity.

Table 3.7. Validation of installed capacity (MW) and power generated (GWh per year) results from different resources, Ethiopia energy sector model

Power source	Actual data (empirical data)				Predicted		Difference 2010	
	2000		2010		2010		Actual-predicted	
	Amount	Share	Amount	Share	Amount	Share	Amount	Share
Installed capacity in MW								
Hydroelectric	401.0	0.94	1,843.0	0.92	1,155.0	0.98	688.0	–0.06
Geothermal	7.3	0.02	7.3	0.00	7.3	0.01	0.0	0.00
Diesel thermal	20.0	0.05	159.0	0.08	22.0	0.02	137.0	0.06
Total	428.3	1.00	2,009.3	1.00	1,184.3	1.00	825.0	
Power generated GWh								
Hydroelectric	1790.0	0.99	3,524.0	0.89	3,377.0	0.94	147.0	–0.06
Geothermal	5.1	0.00	23.6	0.01	52.8	0.01	–29.0	–0.01
Diesel thermal	16.9	0.01	434.0	0.11	155.0	0.04	279.0	0.07
Total	1,812.0	1.00	3,981.6	1.00	3,584.8	1.00	396.8	
Test results for installed capacity				Coeff	SE	t-test	F-test	R-sqr
	γ			0.031	0.035	0.887	0.38	0.68
	θ			–0.050	0.032	–1.460		
Test results for power generated								
	γ			0.03	0.04	0.73	0.46	0.57
	θ			–0.05	0.04	–1.16		

The model results corresponded exactly with the actual level of consumption in 2010. Consumption increased from about 39 million tonnes in 2000 to about 52 million tonnes in 2010. This is because the rate of population growth presumed in model validation was the same as the rate that was used by MoWE to predict the trend growth in solid biomass energy demand. Yet there is a need for innovative policy measures that reduce solid biomass consumption and improve the sustainability of forest biomass extraction.

3.13. Model results and discussion

3.13.1. Electricity demand projection

Peak electricity demand is depicted in Figure 3.10. By 2110 peak demand was projected to reach about 113 GW under a high annual electricity demand growth rate and 42.5 GW under a low growth rate. Annual demand for solid biomass energy was projected to reach approximately 88 million tonnes by 2045.

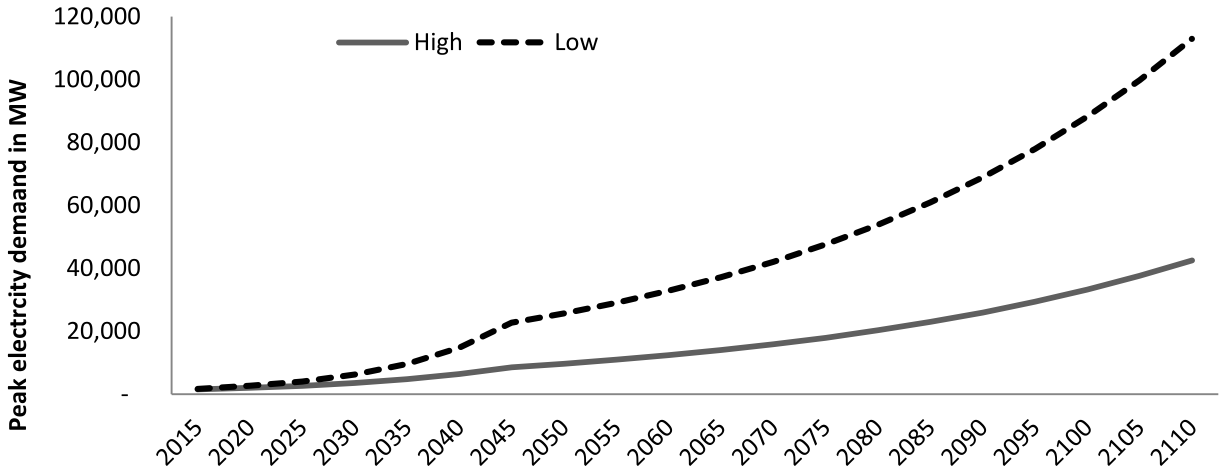

Figure 3.10. Projected peak electricity demand over time, annual electricity demand growth rate of 9% (high) and annual electricity demand growth rate of 6% (low) over 2010-2045, and 2.5% per year over 2045-2110; Ethiopia energy sector model

3.13.2. Shadow price of peak electricity demand

Projected shadow prices for peak electricity demand are depicted in Figure 3.11. Shadow price measures the infinitesimal increases in the minimized cost of energy production due to infinitesimal increases in peak demand for electricity based on the demand constraint at optimal conditions. Shadow price reflects increases in the minimised cost of electricity production when peak electricity demand increases by 1 kWh and is thus an approximation of electricity price.

Ethiopia's actual current electricity price is about ETB 0.572/kWh[15] or US$ 0.031/kWh at an exchange rate of 18.47 ETB/US$ as used in the model. Under a high electricity demand growth rate in 2015 the shadow price was predicted to be about US$ 0.027/kWh, which is only slightly lower than the prevailing electricity price. There are two explanations for the marginal difference. First, in long-term modelling the shadow price reflects the amortized value rather than the market value. Second, higher electricity demand is related to higher prices (Figure 2.11). Ethiopia has relatively high electricity demand, which might push prices up, although Ethiopia's electricity tariff is fixed by government rather than by market interactions of demand and supply.

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[15] Based on http://www.costtotravel.com/cost/electricity-in-ethiopia, accessed on 04/02/2015.

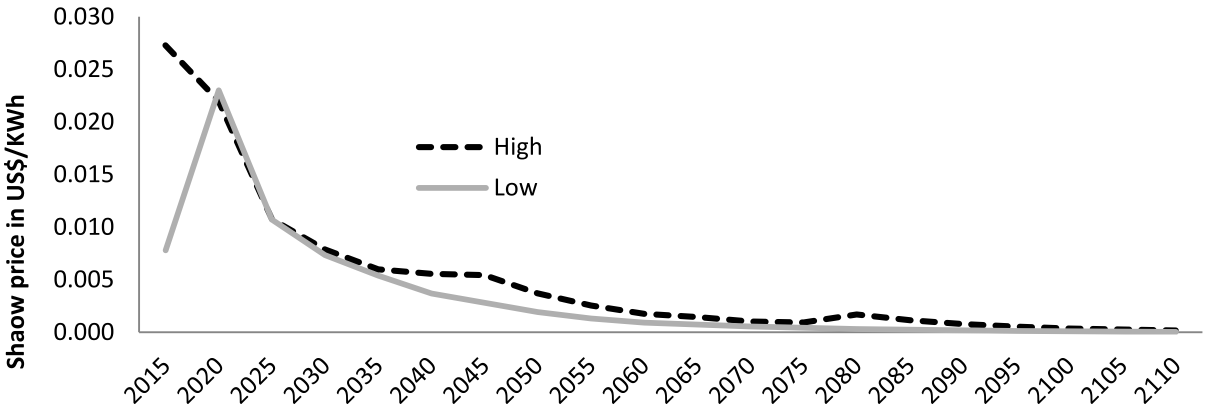

Figure 3.11. Shadow prices of peak electricity demand over time under high and low electricity demand growth rates, Ethiopia energy sector model

3.13.3. Electricity production composition in the baseline model

Figure 3.12 and Figure 3.13 portray electricity production in GWh/year[16] for high and low electricity demand growth rates respectively. Under high electricity demand growth Ethiopia would generate about 388 TWh by 2110 compared to 183 TWh under low growth. Under low electricity demand growth hydroelectric power continues to dominate Ethiopia's electricity mix because it is the cheapest renewable energy source and because it can satisfy projected demand.

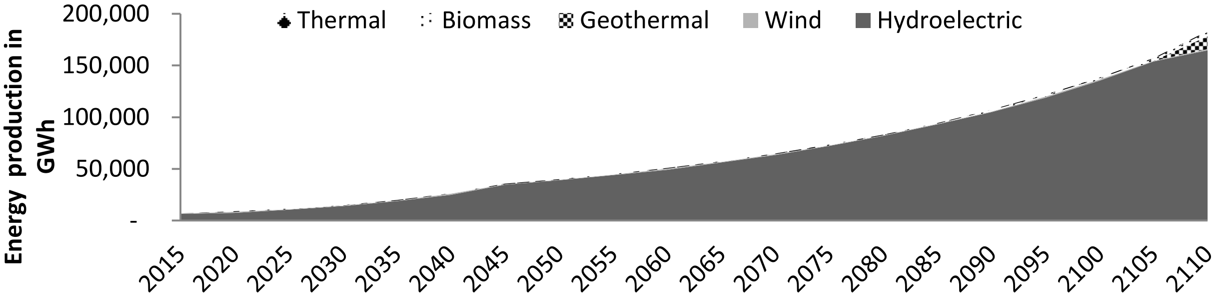

Figure 3.12. Predicted composition of electricity generation over time under low electricity demand, Ethiopia energy sector model

In the case of high electricity demand growth the country would need to increase electricity production, ideally from alternative energy sources. In the latter case geothermal and wind resources were predicted to be fully exploited by 2080 and 2085 respectively, and the country

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[16] Energy in GWh was calculated from MW by using capacity factor of each of the energy sources as $MWh = MW * cap.factor ** 365 * 24hours; or\ GWh = \frac{(MW*capacity\ factor*365*24hours)}{1000}$. The mean capacity factors were 0.53 for hydroelectric energy, 0.79 for geothermal, 0.4 for wind, 0.3 for solar, 0.3 for fossil thermal, and 0.68 for biomass electricity as described for Ethiopia in Böll (2009) and Teshager (2011).

would also produce about 15 TWh from solar energy by 2080. Biomass electrical energy production was projected to commence in 2065 with about 3 TWh, which would grow to full potential of 4 TWh by 2090 (Figure 3.13).

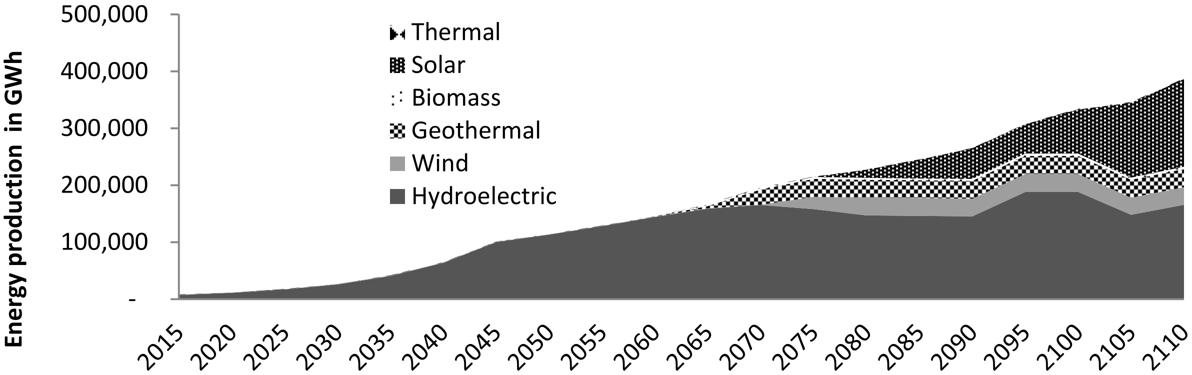

Figure 3.13. Electricity production composition over time under annual electricity demand growth rate of 9%, Ethiopian energy sector model

3.13.4. Implications of technological and efficiency innovations on energy security

3.13.4.1. Effects of technological and efficiency innovations on Ethiopia's electricity production mix

Greater cost reduction rates resulting from technological and efficiency innovation were found to enhance substitution of new energy resources for established energy sources. Projected electricity production by source is portrayed in figures 3.14A-3.14E. Increased cost reductions due to technological and efficiency innovation were associated with increased wind and biomass electrical energy production earlier in the simulation period compared to the baseline scenario (figures 3.14B and 3.14E). Under the high electricity demand growth rate baseline scenario, solar energy production was projected to begin in 2080 at 14.8 TWh per year. However, under the best technological and efficiency innovation scenarios Ethiopia was projected to produce about 14 TWh of energy from solar by 2050-2055 (Figure 3.14C). Approximately 11.5 TWh of energy would be produced from wind by 2045 under the best technological and efficiency innovation scenarios (Figure 3.14B). In contrast, under the baseline scenario additional wind energy production was not projected to begin until 2075. It was projected that Ethiopia would be able to fully develop biomass electrical energy potential of about 4.0 TWh, 1.0 TWh, and 3.1 TWh annually by 2035-2040 under the best, intermediate, and low technological and efficiency innovation scenarios respectively (Figure 3.14E).

Hydroelectric energy production was projected to fall below baseline scenario levels by about 20 TWh in 2110 under the best technological and efficiency innovation scenarios (Figure 3:14A). No additional geothermal energy production would be necessary under the best-case innovation scenario (Figure 3.14D) due to energy substitution. In general, under the best-case innovation scenario it was projected that Ethiopia would undergo a massive shift from hydroelectric to alternative sources such as wind, biomass, and especially solar energy.

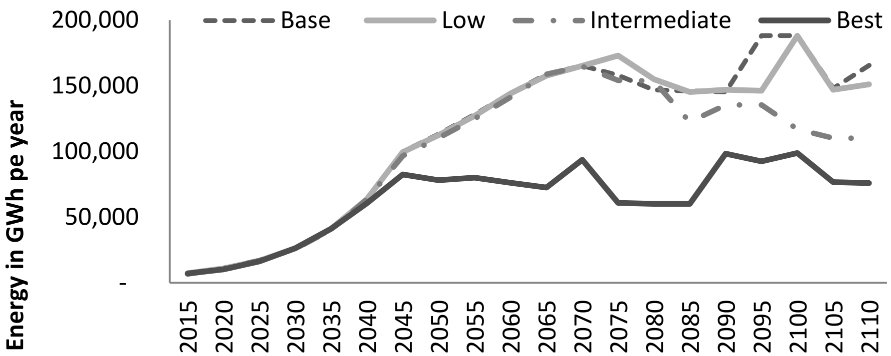

Figure 3.14A: Hydroelectric energy

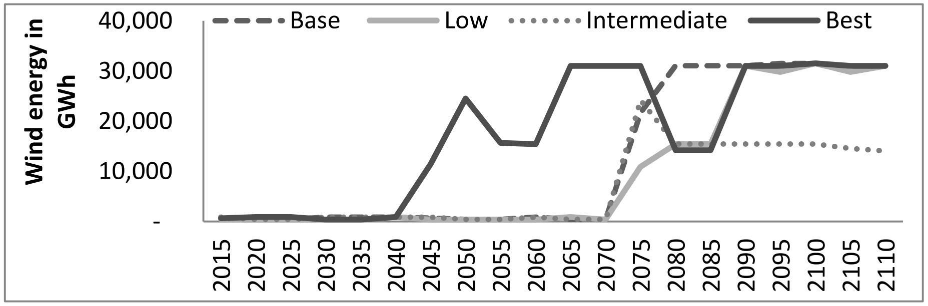

Figure 3.14B: Wind energy

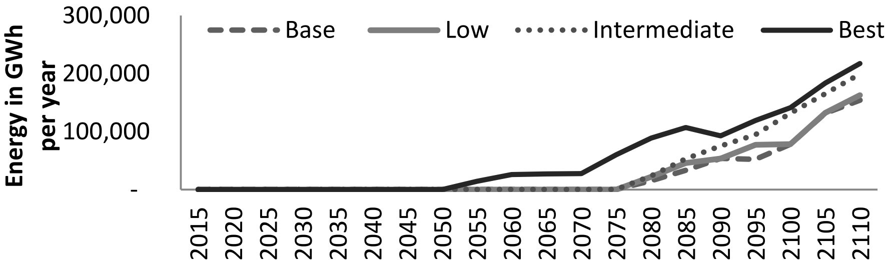

Figure 3.14C: Solar energy

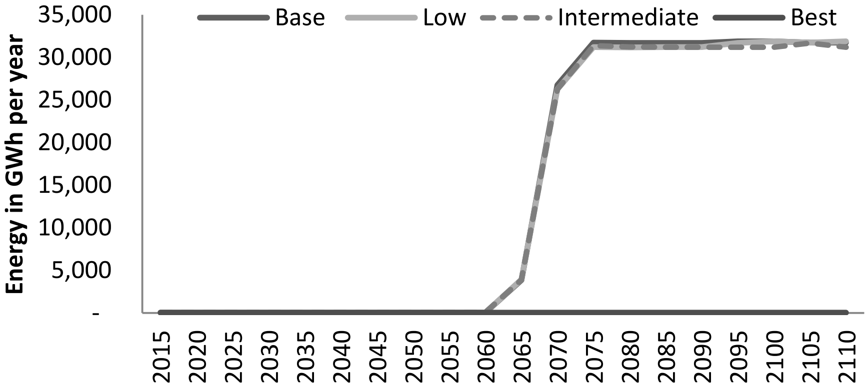

Figure 3.14D: Geothermal energy

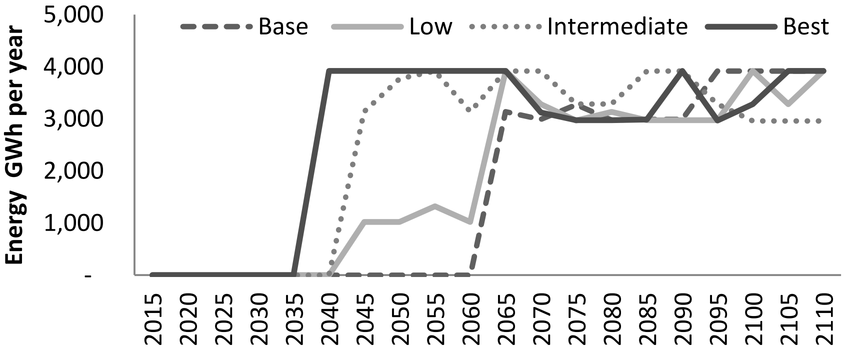

Figure 3.14E: Biomass electrical energy

Figure 3.14. Energy production over time under the three technological growth scenarios and an annual electricity demand growth rate of 9% (GWh/year), Ethiopia energy sector model

3.13.4.2. Effects of technological and efficiency innovations on energy production cost

The model results for different rates of technological and efficiency innovation, and land rental cost, on discounted power generation costs are presented in Table 3.8. Relative to the base–case scenario the model projected that the discounted minimized cost of energy production would decline by about 10% (US$ 0.08 billion) and 18% (US$ 0.42 billion) under high and low electricity demand growth rates respectively. The results indicate that cost reduction benefits increase not only with increases in technological and efficiency innovation rates, but also with increases in electricity demand growth.

Table 3.8. Predicted declines in the minimised total cost of power generation due to the effects of changes in technological and efficiency innovation, and land rental costs compared to the baseline scenario, Ethiopia energy sector model (%)

Technological and efficiency growth rate scenarios	Annual electricity demand growth rate					
	Low demand growth rate (6%)			High demand growth rate (9%)		
	Cost (US$ millions)	Diff.	%	Cost (US$ millions)	Diff.	%
Base	776.0			2,351.7		
Low	760.0	–16.0	–2%	2,268.0	–83.7	–4%
Intermediate	744.8	–31.2	–4%	2,159.0	–192.7	–8%
Best	698.6	–77.4	–10%	1,933.0	–419.0	–18%

3.13.4.3. Effects of technological and efficiency innovations on shadow prices of energy resources

The shadow price reflects reduction in the least cost model solution resulting from relaxing the corresponding resource constraint by one unit. In this sense it shows the decline in the minimized cost of power generation due a unit increase in power generated from that source. Shadow prices of energy resources reflect the change in the cost (Θ) due to a one-unit change in the maximum capacity of resource (Q_{MAX}^{ij}) of plant (i) of energy source (j). Comparison of shadow prices of energy resources is important for considering policy options for optimal renewable energy development. The potential capacity of solar power is immense and non-binding. The shadow prices of the different renewable energy resources are depicted in Figure 3.15. The predicted shadow values of different hydroelectric plants are presented in Figure 3.16. The Gibe IV plant had the highest shadow value with a mean value of about US$ 0.011/kWh, followed by Genale Dewa V, (US$ 0.009/kWh), Tekaze (US$ 0.008/kWh), and Baro (US$ 0.007/kWh). The mean shadow price varied from US$ 0.005/kWh in the base case to US$ 0.001/kWh in the best case. Mean shadow price for all power plant, and technological and innovation growth scenarios was about US$ 0.005/kWh.

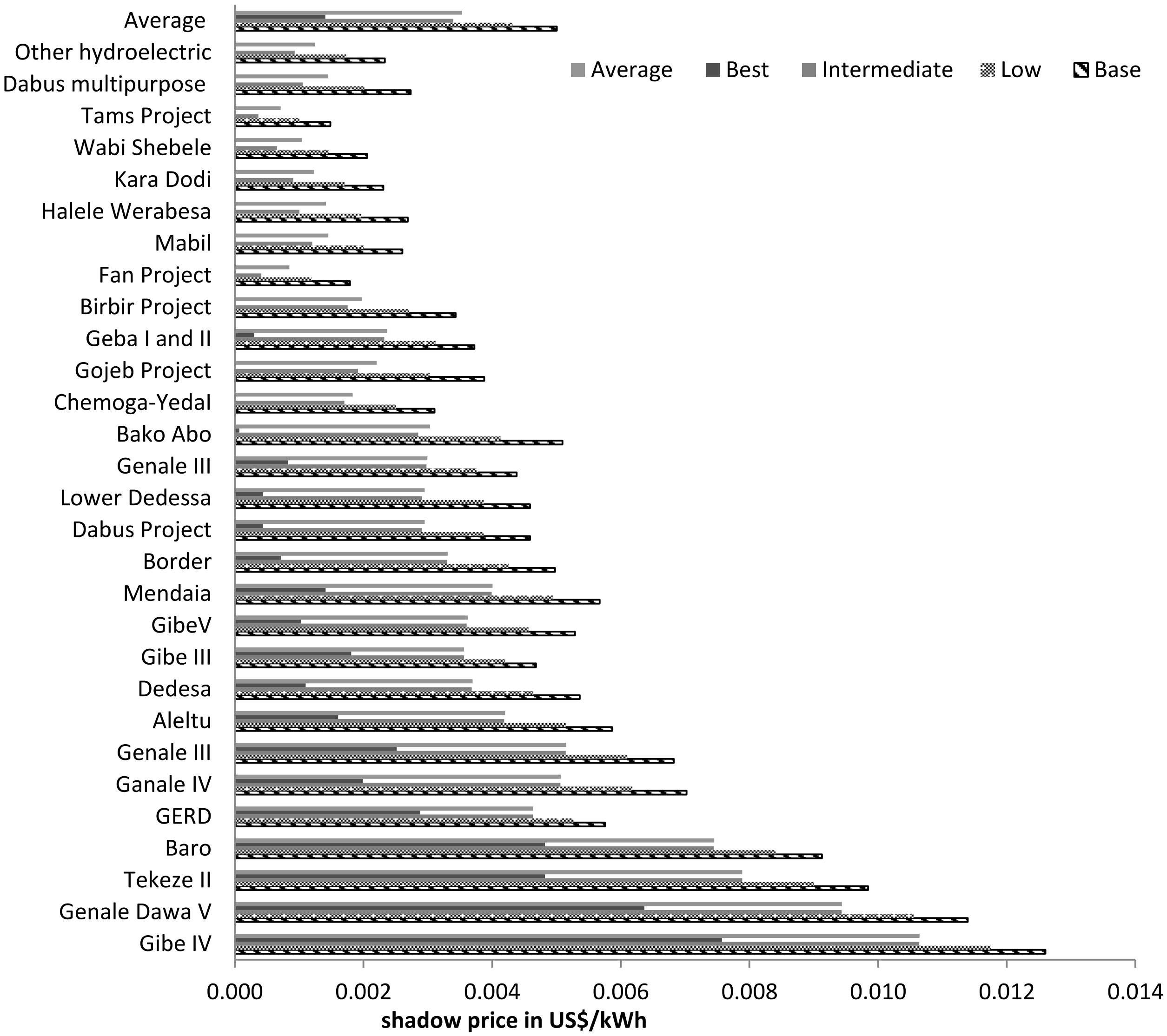

Figure 3.15. Predicted shadow values of resource availability constraints for hydroelectric power plants in the base model, Ethiopia energy sector model (US$/kWh)

Hydroelectric power had the highest mean shadow price at approximately US$ 0.004/kWh, followed by biomass electrical energy at approximately US$ 0.002/kWh, and geothermal and wind power with shadow prices of about US$ 0.001/kWh each. The shadow prices of hydroelectric and geothermal power declined with increases in technological and efficiency innovation rates. This is because technological and efficiency innovations are associated with reduced exploitation of these resources, leaving more of the resource base unexploited (i.e. lowering scarcity or shadow price). Wind and biomass electrical energy shadow prices may increase or decrease depending on the cost reduction level from technological and efficiency innovation and substitution effects. First, increases in technological and efficiency innovation rates reduce shadow prices. In contrast, the substitution effect leaves less of these resource bases unexploited and thus increases shadow prices. Shadow prices of wind and biomass electrical energy generally decline except for a slight increase in the shadow price of biomass electrical energy under the intermediate and best case technological and efficiency innovation rate growth scenarios. The mean shadow price of energy resources declined from US$ 0.003/kWh in the baseline scenario to about US$ 0.001/kWh in best-case scenario, and the overall mean shadow price was about US$ 0.002/kWh.

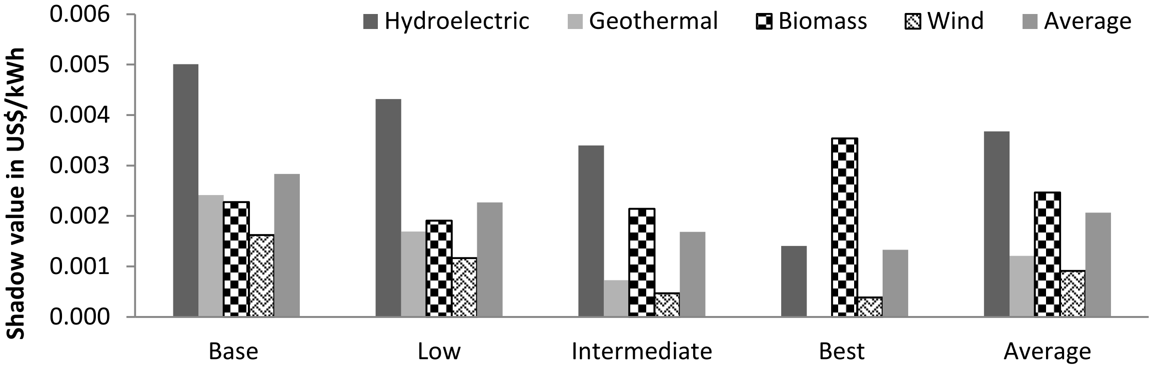

Figure 3.16. Shadow prices of energy resources under the three technological and efficiency innovation growth scenarios with an annual electricity demand growth rate of 9%, Ethiopia energy sector model

The mean predicted shadow price of solid biomass energy use was US$ 0.0006/kWh, which varied considerably among regions (Figure 3.17). Gambella had the highest value at US$ 0.0011/kWh followed by Afar and Benishangual with shadow values of US$ 0.0009/kWh. This shadow value reflects the decline in the cost advantage of biomass production in the respective regions as a result of a one-unit increase in resource availability. It does not include cost of labour requirements. The predicted shadow price represents the shadow value of forest that accounts for the opportunity cost with respect to land. The estimated shadow price of fuelwood collection was about US$ 0.0053/kWh (computed from Table 2.17 in Chapter Two). Thus, the mean total shadow price was estimated to be about US$ 0.0059/kWh, which represents the estimated shadow cost of biomass energy consumption to rural Ethiopian households. Thus, when the labour cost is included in the shadow price solid biomass energy exceeds the predicted shadow price of electricity generation from all other energy sources. However, direct comparison is not possible due to the fact that the shadow price estimated from the energy sector model is an amortized value and subject to discount, but the shadow price estimated in the econometric model presented in Chapter Two was the nominal price in 2011. Market prices of biomass for power generation are expected to be higher than shadow prices for solid biomass energy because the latter only indicates the value of standing forest biomass or, if extracted by households, of the value of household labour costs incurred. The costs of transportation and marketing were not considered. Decentralized renewable energy generation would significantly reduce additional costs and contribute to household welfare gains.

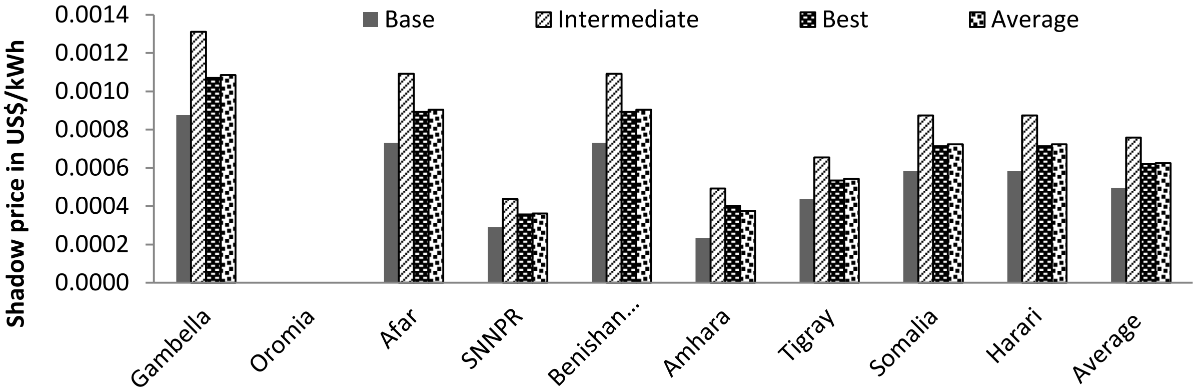

Figure 3.17. Predicted shadow values of resource availability constraints for solid biomass by regions, Ethiopia energy sector model (US$/kWh)

The great variability in the shadow values of biomass availability can be attributed to two possible factors. One is the variation in land availability or opportunity costs, which are relatively low for remote regions and depend on local population density and land constraints. The second is the variability of productivity or biomass yields in each region. Compared to other regions Oromia, SNNP, and Amhara had lower shadow values due to higher land availability (forest and marginal land). These three regions also host most of Ethiopia's population. This hypothesis is supported by the fact that regions like Gambella had high shadow prices or cost reduction advantages compared to relatively low shadow value in major regions like Oromia, which is located near the capital where population density is much greater. Gambella has high productivity or biomass yield compared to other counterpart remote regions.

3.13.5. Energy security implications of climate change or drought

3.13.5.1. Effects of drought on Ethiopia's electricity production mix

There is considerable uncertainty about how climate change may affect energy production in the country; however, hydroelectric power generation is considered to be vulnerable to drought or increased water scarcity. Estimated minimum, mean, median and maximum energy production levels are depicted in figures 3.18A-3.18E. These results conform to recent findings by Robinson et al. (2013) that climate change is likely to have negligible effects on Ethiopia's hydroelectric energy production over the short and midterm, but that adverse effects are more likely to manifest over the long term (Figure 3.18A).

To cope with the effects of climate change on the energy sector Ethiopia should diversify energy production. Model results indicate that energy production diversification is likely to depend on the degree to which drought affects hydroelectric production. Under scenarios of water scarcity increased energy production from alternative resources would occur earlier than was anticipated in the baseline model (Figure 3.18D [geothermal], Figure 3.18B [wind], Figure 3.18E [biomass electrical energy]). Energy production from these resources was projected to vary from the baseline scenario over the 2040-2080 period. In contrast, increases in solar energy production were not projected until after 2075, after wind, geothermal and biomass resources are fully exploited because of the high capital cost of solar (Figure 3.18C).

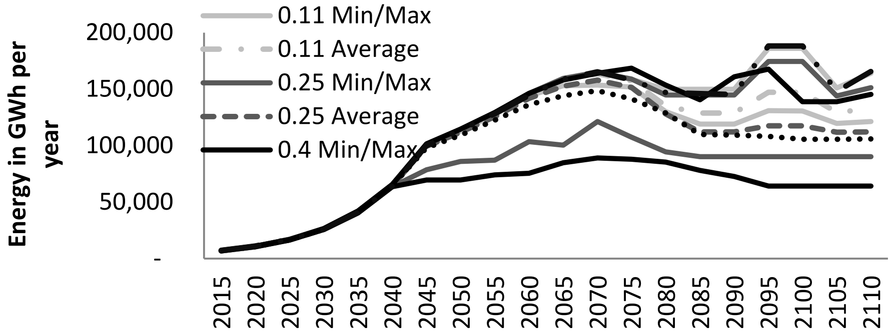

Figure 3.18A: Hydroelectric energy

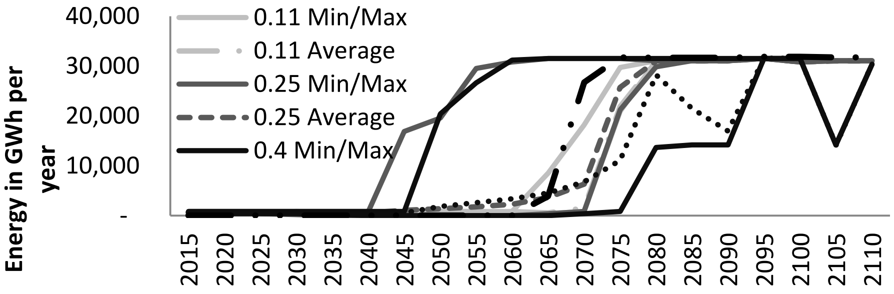

Figure 3.18B: Wind energy

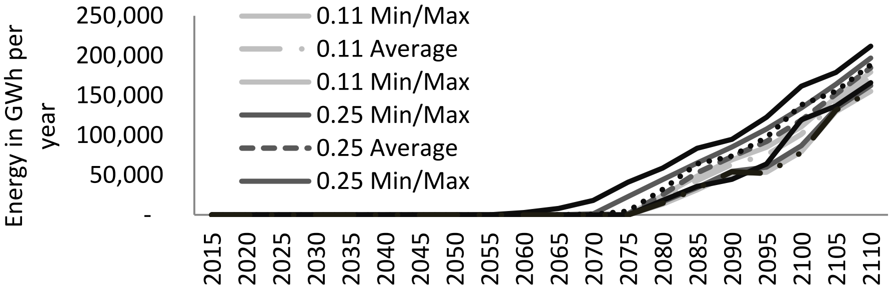

Figure 3.18C: Solar energy

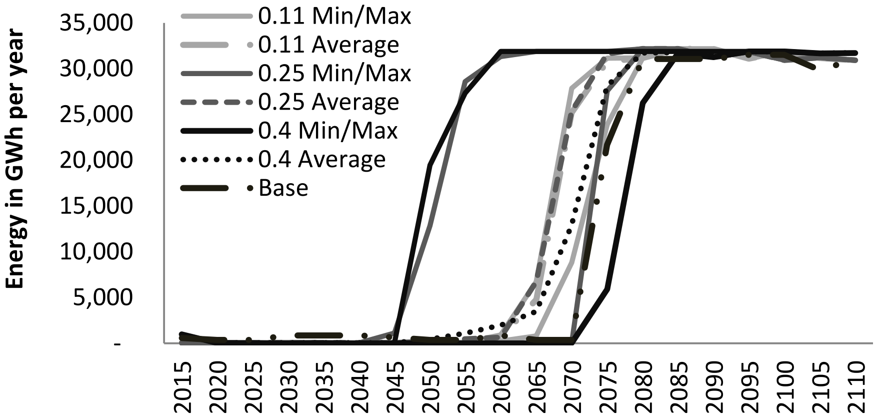

Figure 3.18D: Geothermal energy

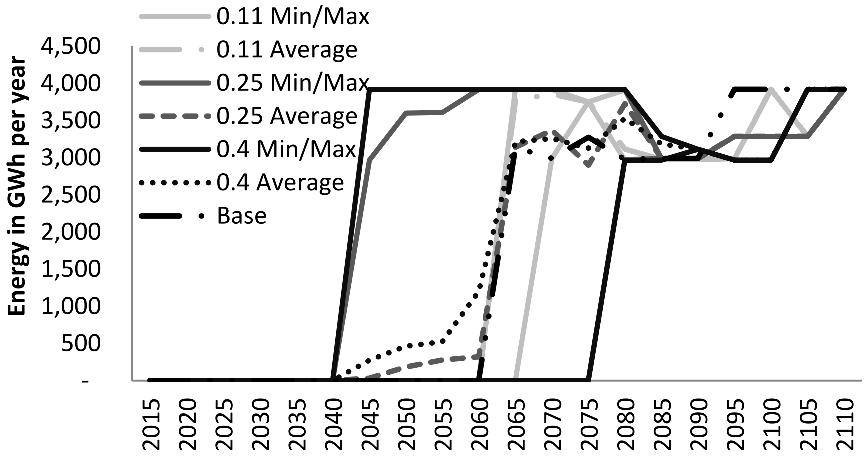

Figure 3.18E: Biomass electrical energy

Figure 3.18. Effects of water availability variability on energy production over time with an annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

3.13.5.2. Effects of drought on energy production costs

The model results for drought on discounted minimised energy production cost relative to the baseline model are presented in Table 3.9. Costs were projected to rise above the baseline model by about 0.1% (US$ 0.002 billion) under a 0.11 standard deviation of water availability, 2.5% (US$ 0.058 billion) under a 0.25 standard deviation, and 7% (US$ 0.16 billion) under a 0.40 standard deviation.

Table 3.9. The estimated minimised cost of energy production for different standard deviation levels of water availability variability with an annual electricity demand growth rate of 9%, Ethiopia energy sector model (US$ millions)

Standard deviation in water flow	Base (A)	Drought scenarios					
		Min	Mean (B)	Difference (B–A)		Median	Max
Base	2,352			Amount	%		
0.11		2,352	2,354	2	0.1%	2,352	2,396
0.25		2,352	2,410	58	2.5%	2,388	2,941
0.40		2,358	2,515	163	6.9%	2,466	3,507

3.13.5.3. Energy source competitiveness: the Levelized cost of energy

The most widely applied measure of renewable energy competitiveness is the ‘levelized cost of energy’ (LCOE), which is the break-even cost of generating power. This cost depends on initial investment costs, annual operating costs, interest rates, and devaluation rates of power generation as described in Eq. (11) in Annex 3.1. The break-even cost calculated by the equation was used as a proxy for price, although the price that consumers pay for electricity is not the same as the predicted retail electrical rates (Branker et al., 2011).

The LCOE value for concentrated solar power was the highest in this context (about US$ 0.189/kWh). Biomass electrical energy and wind were the most expensive sources after solar with LCOE values of US$ 0.122/kWh and US$ 0.102/kWh respectively. Hydroelectric and geothermal had lower LCOE values of about US$ 0.051/kWh and US$ 0.080/kWh respectively (Table 3.10).

3.13.6. Capital subsidies for alternative renewable energy technology development

Upfront capital investment in alternative energy resources like solar, wind, geothermal, and biomass electrical energy remains a significant barrier to more widespread use of these resources in Ethiopia. To improve energy access in remote communities where renewable resources are abundant and financial resources are minimal the optimal policy strategy for Ethiopia would be to provide incentives for private, household, or cooperative associations to invest in renewable resources. Related policies such as capital subsidies could target reducing upfront capital investment costs to make alternative renewable resources competitive with hydroelectric power.

Capital subsidy here refers to the subsidy that the government must pay to private investors to offset the differential capital cost of new energy resources relative to hydroelectric energy. The amount of capital subsidy would depend on plant longevity and differences among technologies based on the annualized present capital cost per unit. Capital subsidies were estimated based in the baseline scenario without technical and efficiency innovation over time.

The estimated capital subsidies required to make alternative renewable energy resources competitive with hydroelectric energy are presented in Table 3.10. The base year capital cost assumptions and plant longevity of each energy type are given in Table A 3.8. The Ethiopian government would need to provide capital subsidies of about US$ 263/kW for solar energy to make it competitive with hydroelectric energy, followed by US$ 118/kW for geothermal, US$ 120/kW for biomass, and US$ 115/kW for wind.

Table 3.10. Estimated capital subsidies required to make alternative renewable technologies competitive with hydroelectricity (US$ millions/kW) and the levelized cost of energy (US$/kWh), Ethiopia energy sector model

Energy sources	Annual present capital cost US$/kW	Capital subsidy (US$/kW)	LCoE US$/kWh	LCoE difference over hydroelectric
Wind	131.43	114.73	0.102	0.051
Solar	280.00	263.30	0.189	0.139
Hydroelectric	16.70	0.00	0.051	
Geothermal	134.76	118.06	0.080	0.030
Biomass	137.14	120.44	0.122	0.072

3.13.7. Sensitivity analysis for fuel-switching effects on power capacity expansion

The elasticity of household fuelwood consumption with respect to the use of electricity was predicted from the econometric results presented in Chapter Two. A 1% increase in electricity consumption would result in fuelwood consumption decline by about 6.7% (Table 2.17). This would reduce pressure on forest resources, benefit society by improving the productivity of households, and reduce both indoor and outdoor air pollution and related public health problems. Conserved forests provide environmental services, sequester CO_2, and provide renewable biomass energy resources that contribute to sustainable energy development. The latter effect was reflected by the model results. Reduced residential demand for solid biomass energy would also liberate increased amounts of biomass feedstock for power generation.

The direct effect of the policy would be the reduction of household demand for fuelwood. This would liberate increased amounts of forest biomass feedstock for power generation. The results indicate that supplying all households with electricity would help the country generate about 10.5 TWh of biomass electricity per year by 2045 from liberated biomass (Figure 3.19), which is about 165% in excess of the base model results.

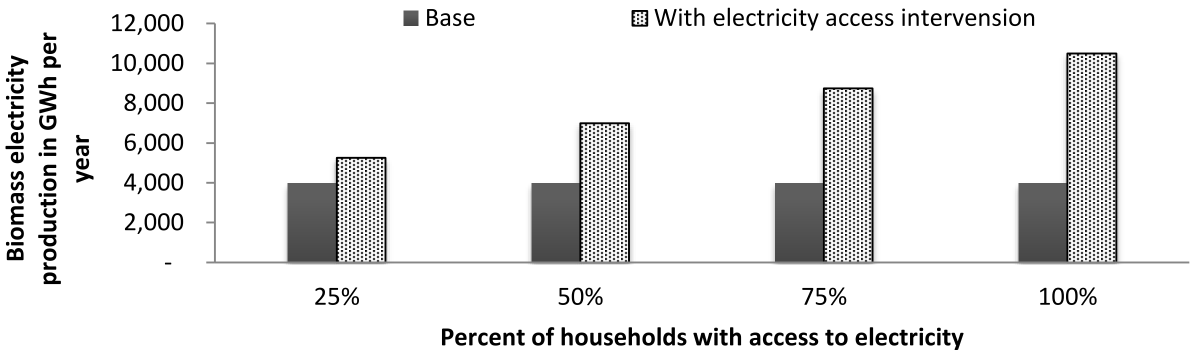

Figure 3.19. **Predicted energy production by 2045 resulting from liberated biomass due to different levels of electricity access (GWh), Ethiopia energy sector model**

3.14. Discussion of the limitations of the model and policy implications

The model is a bottom-up energy sector model, which are based on technological explicitness and are often criticized because they fail to take into account market adjustments such as changes in future demand. The model relies on perfect foresight regarding future energy demand growth. Despite efforts to adequately consider electricity demand growth rates (using high and low growth rate scenarios) future electricity demand remains uncertain, as it will depend on various factors that could not captured in the model.

There are many caveats regarding the results of this model that future research efforts should take into account. Greater capacity and energy production from alternative technologies only appear to increase over the long term. This is because substitution was allowed among energy sources solely on the basis of cost competitiveness. In the model, only the upper limits of resource availability potential for each plant and energy source, and a non-negativity constraint, were defined. Unlike most dynamic linear programing models on energy systems, a positive lower boundary was not imposed for any of the energy resources except for the 561 MW capacity of the Gibe III hydroelectric plant (which is in the final stages of construction) and the current wind capacity for the country.

Alternative renewable energy sources had high per unit capital costs in the baseline year (2010) relative to hydroelectric power, which is the cheapest, most abundant, and tested renewable energy source in Ethiopia. Despite recent evidence of sharp reductions in the capital costs of many renewable resources, especially solar, the cost parameters could not be updated because the model parameters were all based on base year values. Cost coefficients for other renewable technologies, especially solar, are not available for Ethiopia. The relevant literature was reviewed to determine per unit costs for wind, biomass, and geothermal energy from plants currently under construction in the country. Recently Ethiopia has begun to adopt alternative technologies, which will provide data for future research efforts.

Technological innovation has already resulted in drastic reductions in the cost of hardware for alternative energy resources. Alternative scenarios were evaluated to estimate the effects of technological and efficiency innovations, but these changes were not sufficient to make alternative technologies competitive with hydroelectric power in the short to midterm. The alternative scenario analyses addressed uncertainties related to cost coefficients, but were constrained by the lack of current data on alternative resources, particularly for solar energy, which has exhibited drastic cost declines in recent decades. This is because these technologies have only been recently applied in Ethiopia and the cost assumptions from 2010 would not reflect the current reality.

There is great uncertainty about how climatic change will affect future energy production in Ethiopia. The effect will partly depend on demand growth rate and changes in the frequency and severity of drought. Moreover, the effects of climate change are debatable. In the Ethiopian highlands it has been suggested that precipitation may increase rather than decrease, which may actually increase water availability for hydroelectric power generation. However, if precipitation increases only occur during the rainy season this may not translate to increased hydroelectric energy production as water scarcity normally arises during the dry season. Increased precipitation may not necessarily benefit hydroelectric production unless it occurs during the dry season. Increases in the intensity of precipitation may increase the risk of flooding, siltation, and sedimentation, which have direct negative effects on the capacity of hydroelectric reservoirs. Ethiopia is currently building a large hydroelectric project. The classic investment maxim about ‘putting all of your eggs in one basket’ or increasing risk of financial loss also applies to energy security, as nearly complete dependence on large hydroelectric reservoirs may entail enormous energy security risks. Potentially there could be many adaptation measures for coping with climate change or drought.

Some researchers suggest that the construction of small–scale hydroelectric projects would enable the country to mitigate the risks of climate change or drought. While the construction of small hydroelectric plants may increases the country’s capacity to adapt to the effects of climate change or drought, it is also true that per unit costs of generating power from small dams is significantly higher than from large hydroelectric plants according to national statistics on existing plants. In contrast, small hydroelectric plants designed as decentralized power providers for rural communities require less transmission and distribution networks and therefore less related costs.

To date there are two proven primary adaptation measures to drought in Ethiopia. First, the country could increase the use of fossil thermal to cope with power rationing or blackout. Past trends indicate that when the country faces shortfalls in electricity, private and governmental organizations increase their use of diesel generators. EEPCO data also show evidence of increased fossil thermal use in dry years (e.g. 2007-2009 in Figure 3.2). One limitation of the model is that the lack of detailed data on non-renewable energy resource potential of the country prevented incorporating relevant parameters. Ethiopia may be able to explore and exploit its fossil resources more cheaply than the current costs of importing them. In this modelling exercise it was assumed that fossil thermal electricity production depends on fixed annual growth rates. Due to the lack of detailed data on thermal plants, the different fuels (gas, coal, and diesel) were not identified. Despite technological and efficiency improvements among alternative energy resources, electricity generation from non-renewable resources remains the cheapest option for Ethiopia over the short and midterm. Nevertheless, the CO_2 emissions of electricity generation, which were not considered due to the limited scope of the research, should be taken into account to reach conclusive findings about the net benefits of alternative energy resources, not only economic considerations, but also environmental aspects. Over the long term the Ethiopian federal government plans to develop nuclear energy capacity, which would significantly affect potential energy diversification pathways.

The most important large-scale long-term measures implemented to cope with impact of drought were nationwide afforestation and natural resource (land, soil, and water) conservation programmes. These measures have been pursued extensively as part of the country's green economy strategy to rehabilitate degraded land, communal graxing areas, and river basins. These measures are crucial policy measures that can reduce risks to hydropower arising from flooding, siltation, and sedimentation, which reduce the capacity of hydroelectric reservoirs.

In this modelling exercise the climate change or drought scenario was applied using a range of standard deviation values (0.11-0.40) to capture uncertainty. The model permitted the measurement of the economic costs of adaptation in terms of increases in the cost of energy diversification through alternative renewable resources as a means of coping with climate change or drought. The results revealed that increases in the cost of energy production could be expected, which is relatively straightforward. The country would need to generate more electricity from relatively expensive renewable technologies to meet projected demand in the face of shortfalls in hydroelectric energy resulting from climate energy or drought. Climate change is a dynamic process and its actual impacts on electricity generation are not yet empirically determined.

Two options were investigated in this analysis: capital subsidies to make alternative technologies competitive with hydroelectric power and innovations in technological change and efficiency improvement. The former may be an effective approach in the short term, but would not be as effective over the long term relative to the latter. First, subsidies could promote household or private investment in alternative energy technology projects, but such measures only transfer the cost to the government. Second, the government could take measures to create a more secure investment environment, but such efforts may not directly result in technological and efficiency innovations that reduce per unit costs and that influence the nation's energy development. Households and other small-scale private investors are not likely to be able to invest in R&D, technological advances, improved efficiency, or skill development. Investment in these activities is often considered the government's role. Third, government budgets in developing countries are typically a limiting factor. Eventually, a more efficient strategy for reducing the risks associated with the effects of climate change would be to invest in technological and efficiency innovations or adaptability, and in capacity building or training. Alternative renewable energy sources can offer long–term environmental, economic, and public health benefits. The model results were based on the presumed economic benefits of technological and efficiency innovations in terms of the shadow prices of resources. In general, shadow prices increase with greater rates of technological and efficiency innovation, reflecting reduced resource scarcity and conforming to the hypothesis that technological and efficiency advancements drive economic growth, particularly with respect to energy production. Nonetheless, there is debate in the literature about the ‘rebound effect’ of technological and efficiency innovation, and about the degree to which they result in cost reductions and whether they increase energy consumption, which in case of the latter may partially offset any positive gains (Zein-Elabdin, 1997; Turner, 2012). Appropriate empirical research attention should be given to these issues in the future.

3.15. Conclusion and policy recommendations

Ethiopia needs to invest in renewable energy resources to ensure green energy development, achieve poverty alleviation, and improve energy security; however, such an effort is hindered due to the high capital costs of these alternative energy resources. Technological and efficiency innovations are expected to have important roles in future energy investment pathways. Policy measures could directly target innovation through support for R&D or the development of local skills and technical capacity. In a world of constrained resource availability, technological and efficiency innovations can contribute to growth. Increases in cost reductions from technological and efficiency innovations were associated with decreases in the shadow prices of energy production. This reflects the assumed economic benefits of technological and efficiency innovations due to their role in reducing resource scarcity. Appropriate policies would contribute to all four dimensions of energy security: greater affordability, accessibility, availability, and acceptability of clean energy to both rural and urban populations, and also offer ‘green growth’ opportunities. The public role would be to create a secure environment for private investors or decentralized renewable energy investment. Policy support for renewable technologies should be directed at closing technical, financial, and efficiency gaps that exist in the country’s energy sector. The government could also offer incentives for technological and efficiency innovation, R&D, and human skill development with respect to renewable energy use policy tools such as capital subsidies that enhance the competitiveness of alternative energy sources.

Chapter Four

Institutional arrangements, collective actions, and national strategy options for decentralised clean energy generation and use in remote communities of Ethiopia

4.1. Introduction

Econometric approaches and a mathematical model were presented in Chapter Two and Chapter Three respectively to examine issues related to biomass energy use, both from a household perspective and within the context of the nationwide energy sector. Various issues related to integrated agroforestry, the sustainable use of renewable energy resources, technological and efficiency innovation, and energy substitution were mentioned. A comprehensive energy diversification and substitution effort should seek to develop sustainable renewable energy in a way that helps to address the energy crisis, foster poverty reduction, promote green economic growth, improve local livelihoods, and support forest restoration.

The energy crisis in rural Ethiopia is complex despite the fact that the country is endowed with a diversity of abundant renewable energy resources. This is because community level efforts to tap their existing resource potential have been hindered by the lack of technical, infrastructural, and economic resources. For bridging the gap between supply and demand with sustainable and affordable energy, increasing attention has been given to decentralized approaches.

Decentralized community-based energy development offers greater opportunities for local economic development and improving rural livelihoods (Klagge and Brocke, 2012). Such efforts can improve access to low cost energy, and contribute to rural economic development (Alanne and Solari, 2006; UNDP, 2011). Decentralized community-based energy can be reliable, efficient, clean, and environmentally responsible energy options for remote communities (Alanne and Solari, 2006; Bluemling and Visser, 2013). In developing countries, however, there are many uncertainties as well as formidable institutional weaknesses and collective action barriers that hinder decentralized energy development. For instance, a study of decentralized biomass based gasification efforts in India identified a problem described as the "club dilemma" that has resulted in discontinuation of some efforts (Bluemling and Visser, 2013). This problem arises from "fluctuating numbers of service users, the club that faced the decision to either expand the system to new members, or to reduce the services provided". Successful decentralized energy development efforts may require restructuring traditional institutions and designing an appropriate strategy for mobilizing collective action of different actors. This should contribute to the design of effective political, social, economic, and market institutions for more sustainable use of locally available renewable energy resources.

A study from the UK found that a main driver of decentralized energy efforts is environmental concern and awareness about the impacts of GHG emissions from fossil energy use (Chmutina et al., 2014). Most of the related literature indicates that financial incentives or the cost effectiveness of decentralized energy are important factors (see Table 4.2). Related research findings have emphasized the simultaneous roles of decentralized renewable energy approaches as both a means of mitigation and as adaptive measures to address the effects of climate change (Venema and Rehman, 2007). Such approaches offer tremendous opportunities because there are technologies capable of making more effective use of many locally available resources (Miller and Hope, 2000).

Strategies for the promotion of the sustainable use of biomass and other renewable energy resources for community energy needs in the remotest areas in Ethiopia were investigated. More specifically, the concept of community-based decentralized rural energy investment (DREI) for sustainable development and its potential links to participatory forest management (PFM) were elaborated upon. In recent years the delegation of forest resource management rights to local communities through PFM schemes has attracted growing attention worldwide. Why is there such interest in participatory forest management? Traditional fuelwood use forms the backbone of national energy use in many developing nations and the efficiency of traditional use can often be improved considerably. The roles of forests and sustainable forest management in climate change mitigation, adaptation, and carbon sequestration have also received increasing recognition. Extensive research on PFM in Ethiopia (Terefe, 2002; Senbeta, 2006; Temesgen et al., 2007; Gobeze et al., 2009; Kassa et al., 2009; Tesfaye et al., 2011; Engida and Tashoma, 2012) and elsewhere across the developing world (Campbell, 2006; Abwoli et al., 2008) have found that effective participatory forest governance institutions can have crucial roles in improving the sustainability of forest resource use as well as the livelihoods of local resource users.

There has been relatively little effort made to link PFM to the development of modern decentralized energy options for remote communities. The need to modify existing Ethiopian rural energy institutions in order to develop effective decentralized energy for remote communities has been identified (Wolde-Ghiorgis, 2002). Mulugetta (2008) assessed the bottlenecks in Ethiopia’s sustainable future energy development effort and discussed technical capacity and institutional issues. That study suggested that Ethiopia should invest in its own capacity development to improve access to clean energy by rural households and communities. A major challenge to Ethiopian energy security is rooted in capacity barriers, including technical, economic, and institutional weaknesses from both the demand and supply sides (Guta, 2012b).

This chapter features the investigation of the institutional context of decentralized renewable energy development in rural areas of Ethiopia. The empirical analyses were based on the results of focus group discussions and a cost-benefit analysis of different biogas energy options. Statistical information on household energy use, time spent on energy resource collection and the costs of institutional and private biogas systems were used for this analysis. The following relevant questions were addressed: What strategies and institutional options are likely to be effective for achieving sustainable decentralized community energy development in Ethiopia? How could the development of decentralized energy generation be linked to PFM measures, or scaled up and sustained? What are the barriers, challenges, opportunities, and critical issues facing decentralized energy development in Ethiopia? What do the results of the comparison of institutional and private biogas systems portend for the future development of such efforts in Ethiopia?

4.2. Energy access in rural Ethiopia

The distribution of rural Ethiopian households by the type of energy used for cooking and illumination is presented in Table 4.1. An overwhelming majority of sample households relied on kerosene lanterns for illumination purposes. There was a significant downward trend in the percentage of households dependent on kerosene, from 80% in 2005 to 64% in 2011. This was accompanied by increased access to electricity through the use of solar battery charging systems. The percentage of households that utilized either electricity, liquefied petroleum (LPG), battery powered devices, and other energy sources for illumination increased from 1% to about 21% over the 2005-2011 period. The percentage of households with access to electricity through either private or shared schemes also increased from 0.7% to about 5% over the same period. Steep hikes in prices and increasing awareness of the environmental pollutants associated with fossil fuels have contributed to increasing household demand for clean energy alternatives. The poorest citizens cannot afford to purchase kerosene and continue to be dependent on traditional forms of biomass energy.

The Central Statistical Agency (CSA) estimated that about 14% of Ethiopian households used neither kerosene nor electricity in 2011, but rather fuelwood for household illumination (CSA, 2012). The percentage of households that used kerosene for illumination purposes was approximately 75%. A steep rise in the price of fossil fuels, particularly kerosene, would make them cost prohibitive in the face of meagre household incomes. From 2005 to 2011 fuelwood consumption among Ethiopian households rose from 85% to 91% for cooking purposes and dropped from 19% to 14% for illumination. The percentage of households that utilized either cattle dung or crop residues as their primary energy source for cooking purposes declined from 13% in 2005 to 8% in 2011.

Table 4.1. Rural Ethiopian household energy resource use for cooking and illumination over time (%), 2005-2011

Fuel type	Cooking			Illumination		
	2005	2011	Difference	2005	2011	Difference
Fuelwood	84.7%	90.8%	6%	18.5%	14.1%	–4.40%
Charcoal	0.2%	0.2%	0%			0.00%
Leaves, cattle dung, crop residues	12.7%	8.4%	–4%			0.00%
Kerosene	0.2%	0.2%	0%	80.1%	64.4%	–15.70%
Electricity				1.2%	4.9%	3.7%
Others (battery powered devices, liquefied petroleum gas, etc.)	2.5%	0.2%	–2%	0.1%	16%	15.9%

Source: CSA (2012)

Ethiopia's rural electrification programme is supported by the Universal Energy Access Programme (UEAP), which is funded by the World Bank and regulated by EEPCO. The programme works to improve the availability and adequacy of electricity in the most energy deprived rural communities to reduce environmental degradation associated with rural energy use, to improve the supply and efficient use of energy resources, and to reduce barriers to the widespread use of renewable energy in those areas (World Bank energy access project, 2013). A recent unpublished MoWE report indicates that this programme has expanded access to clean solar power in rural communities of the country through loan funded purchases of 25,000 solar panels that were primarily distributed throughout Oromia (26.65%), SNNP (24.6%), and Amhara and Tigray (24.9%),. Despite this progress the gap between demand and supply remains huge.

Another renewable energy resource that is commonly featured for both improved energy access and agricultural productivity or food security interventions is biogas. The National Biogas Programme of Ethiopia **(**NBPE) supports rural biogas energy projects by providing subsidies and building local capacity. The programme is operated by the Ethiopian Rural Energy Development and Promotion Centre (EREDPC) and SNV. Information from the EREDPC indicates that implementation of the programme has been slowed down by various delays. Though the potential opportunity of harnessing renewable sources for mitigating the rural energy crisis and improving food security is massive, there are complex challenges to overcoming the technical, institutional, managerial, regulatory, financial, capacity, and other issues related to the lack of required infrastructure and a very dispersed rural population.

Demand side management policies can be effective for addressing rural energy problems. The MoWE (2013) recently initiated the National Improved Cook Stoves Programme with the goal of distributing 9.4 million improved efficiency cook stoves over a 4-year period (2013-2016). But the econometric results presented in the previous chaper indicate that improved cook stove use would have a limited impact on household biomass energy use, although the health benefits of reduction in IAP may justify their broader use. However, the improved stove market is struggling from a lack of demand, which is making it a less attractive investment for private businesses (Accenture Development Partnerships, 2014). That report identified major challenges to the broader distribution of improved stoves such as: “high stove prices, logistical distribution challenges, product gaps, ineffective markets and limited distribution networks, the lack of appropriate skills and capabilities, and limited attractiveness for private investors.”

4.3. Technological and institutional issues

4.3.1. Decentralized renewable energy technologies

In recent years there has been greater attention on the use of a broader diversity of renewable energy resources for addressing energy access problems in remote areas of developing countries. In addition, decentralized renewable energy investement efforts are expected to contribute to poverty reduction, environmental protection, and the improvement of energy security. There is a wide variety of technologies that are suitable for decentralized renewable energy resource approaches, including: solar PV, CSP, various forms of biomass use (gasified, co-firing, biogas, biodiesel, ethanol, etc.), wind, small-scale hydroelectric, and hybrid systems of different energy resources. There is wealth of studies on decentralized renewable energy or the ‘smart grid’ approach. Relevant literature sources are listed in Table 4.2.

Table 4.2. Review of literature on decentralized renewable energy technology

Author(s)	Technology	Research location
Sivachandran et al. (2007)	Wind/diesel/solar	India
Bekele and Palm (2010)	Solar/wind hybrid	Ethiopia
Bazmi et al. (2011)	Oil palm biomass	East Asia
Thiam (2010)	PV/grid/wind	Senegal
Deichmann et al. (2011)	Stand–alone vs. grid	Ethiopia, Ghana and Kenya
Hiremath et al. (2010)	Decentralized biomass power/ gasification/solar PV	India
Levin and Thomas (2012)	Centralized vs. decentralized	Botswana, Uganda and Bangladesh
Chaurey and Kandpal (2010)	Solar PV	India
Narula et al. (2012)	Mini-grid and stand-alone	South Asia
Mondal and Denich (2010)	Wind/diesel/photovoltaic (PV)	Bangladesh
Yadoo and Cruickshank (2012)	Biomass gasifiers/mini-grids/micro-hydroelectric	Nepal, Peru, and Kenya
Nouni et al. (2007), Palit et al. (2011)	Decentralized biomass gasifier	India
Mahapatra and Dasappa (2012)	Solar PV/biomass gasifier/grid	General
Mohammed et al. (2013)	Decentralized agricultural biomass	Ghana
Klagge and Brocke (2012)	Biogas and wind value chains	Germany

The studies listed in Table 4.1 discuss the cost effectiveness, technical feasibility, and economic benefits of different renewable resource or hybrid technologies. Bekele and Palm (2010) conducted a feasibility study for a solar/wind hybrid system used for supplying electricity to communities that are isolated from electrical grids. They used net present cost to assess optimum solutions based on wind speed, PV costs, and diesel prices. Thiam (2010) studied the cost of decentralized micro grids versus traditional grids for PV and wind by computing the LCC values for each option and found that decentralized PV was cost competitive compared to grid systems for remote rural areas of Senegal. Another study of three African countries used spatial modelling and cost estimates to determine where stand-alone renewable energy generation was cost effective compared to a centralized grid system (Deichmann et al., 2011). Mondal and Denich (2010) studied hybrid systems for decentralized power generation in Bangladesh.

Hiremath et al. (2010) described a ‘decentralized energy planning’ (DEP) project in India as an option for meeting rural and small-scale energy needs in a reliable, affordable, and environmentally sustainable way. Based on a review of different case studies of distributed biomass power generation and solar PV systems in India, they concluded that “small-scale power generation systems based on renewable energy sources are more efficient and cost effective.” Yadoo and Cruickshank (2012) examined the advantages and disadvantages of using renewable energy technologies for rural electrification in developing countries and found that mini-grids powered by biomass gasifiers and micro-hydroelectric plants were the best options due to their relatively lower LCC values. Other studies have emphasized the importance of public policies that promote renewable energy. For instance, Glemarec (2012) examined the role of public instruments for promoting private financial support for projects that improve the sustainability of off-grid energy access and found that private sector financial support could help provide decentralized energy access for the poor.

Other literature has emphasized the potential developmental role of decentralized renewable energy. As decentralizing energy involves scaling down energy development to sub-national or smaller scales (Kumar et al., 2009) it offers many socio–economic developmental opportunities. Bazmi et al. (2011) investigated the progress and challenges of sustainable decentralized electricity generation from oil palm biomass. They found that in addition to economic gains in the cost reduction of imported fossil fuels, the development of bioenergy could result in energy security for East Asian countries by diversifying their energy supply and by increasing rural job creation and incomes in rural communities. Another study indicated that through technological and institutional 'leap-frogging,' Africa could harness opportunities for augmenting renewable energy initiatives by learning from the experiences and lessons drawn from South Asia and Latin America (Kammen and Karibu, 2008). A study on the decentralized Soltau bioenergy/biogas and Emden wind projects in Germany underscored the importance of institutional restructuring, supportive governance structures, and the role of trusting, cooperative relationships among the diverse actors (Klagge and Brocke, 2012). That study also found that the decentralized electricity generation value chains offer income and employment for specialized firms and other actors.

4.1.1. Institutions and collective action theories

Institutions are used to connect local, national, and international governance initiatives, and to facilitate participation among the coalition of different actors and stakeholders that share common objectives. Since North (1990), the 'new institutional economics' (NIE) concept has been used to examine governance structure for natural resources and particularly for common or shared resources (Andersson and Agrawal, 2011). As a result it has been argued that, "beyond shaping human-human interactions, institutions can have a considerable role in shaping human-nature relationships" (Stellmacher and Mollinga, 2009). Institution is defined as a special type of social structure that determines change of individual agent behaviour, including the changes to their purposes or preferences (Hodgson, 2006). Institutions function on the basis of rules that are "embedded in the shared habits of thought and behaviour of the people who created them" (Kilpinen, 2000; Hodgson, 2006). Institutions sharpen the way societal behaviour evolves over time and are a key factor for understanding historical changes (North, 1990).

Institutions that govern communal resource use are expected to be most productive if they justify the specific setting through 'polycentric structures and rule systems' (Ostrom, 2009). In this regard, there is general consensus in the literature that institutions are the among key decisive explanatory factors in governing human behaviour related to environmental resource use and scientists suggest the use of incentives and disincentives in order to shape human behaviour, especially with respect to forest resource use, management, and conservation (Agrawal, 1995;

Agrawal and Yadama, 1997; Bodin et al., 2006; Stellmacher and Mollinga, 2009). NIE has a potential role in shaping social behaviour related to communal resource use and thereby improving sustainability and the generation of livelihood benefits. Institutions that deal effectively with environmental service provision are missing in many developing country contexts, resulting in imperfections due to the fact that commercial markets are unable to value these resources appropriately. Thus, policies must correct market and governance failures, and improve management coordination to internalize both intended and unintended externalities, thus supporting collective action, participatory outcomes, negotiation, and reducing social conflict.

A major problem in communal resource use is heterogeneity among resource users and the often divergent interests that arise in the process of collective action formation and implementation, which can lead to potential conflict. This heterogeneity may impede cooperation if it leads to rent seeking behaviour by some participants or results in a 'free-riding' problem-when certain stakeholders enjoy the benefits of collective action without contributing or fulfilling the responsibilities expected of them by the group or greater society. Thus, it is expected that the more homogenous stakeholders are in terms of ethnicity, religion, economic status, etc., the more feasible it is to reach a cooperative outcome. Studies have found that people often simply refuse to work with others outside of their particular socio-ethnic group, as the interests of one group often conflict with others, which may have negative consequences that deter cooperation among members of heterogeneous communities (Alesina and La Ferrara, 2000; Bandiera et al., 2005).

Studies have also found that 'corrective measures' in terms of both 'monetary and non–monetary sanctions' can be an effective means of limiting deviant behaviour, and that rewards to those that comply with expectations can increase the level of cooperation (Fehr and Gachter, 2000; Cardenas, 2003; Masclet et al., 2003; Bandiera et al., 2005). The likelihood of divergent interests is normally expected to increase with the number of people or heterogeneity among groups or individuals within cooperative associations (Naidu, 2005). That study identified three forms of heterogeneity that affect natural resource use 'wealth, identity and interest.' A lack of consensus and competition among stakeholders often leads to conflict and 'disputes over natural resource use' (Matiru, 2000). Bardhan (2000) found a significant correlation between group size and the success of collective action. Naidu (2005) found that high levels of wealth heterogeneity reduce natural resource user cooperation as it affects the ability and incentives to cooperate. Thus increased inequality in the presence of market imperfections and decreasing returns on productive assets may reduce aggregate contributions (Bandiera et al., 2005). Heterogeneity of cooperative stakeholders also presents a problem for enforcing effective sanction mechanisms, as well as for shaping collective action to regulate self-interested behaviours (Banerjee et al., 2004). A study from India and Nepal indicated that participatory forest governance often results in the exclusion of certain social groups, particularly marginalized women (Agrawal, 2001; 2010). Through societies or associations, local resource user groups can create a sense of shared responsibility for the proper management of those resources through collective action (Ostrom, 1990; Agrawal and Gibson, 1999). There are two basic objectives of implementing participatory or joint forest management; (i) to improve the sustainability of resource management, often to reposition those who have traditionally exploited resources unsustainably as the stewards of the forests and forest resources they rely on, and (ii) to improve livelihood strategies or outcomes.

There are both pessimistic and optimistic perspectives regarding decentralized forestry policies in developing countries. Proponents have argued that decentralization of property rights and forest management responsibilities to community and government level decision makers will assist to develop and operate institutions in ways that are consistent with the needs and desires of local forest resource users (Blair, 2000; Conyers, 2006; Rondinelli, 2006). A six–country study by Blair (2000) found that participation and accountability have significant roles in promoting democratic local resource governance. In contrast, pessimists have argued that in developing countries decentralized forest resource governance often leads to increased deforestation as local governments may lack the required resources (human, physical and capital) to be effective in governing natural resource use (Larson, 2002; Andersson, 2004; Gregersen et al., 2005; Abwoli et al., 2008).

Over last half a century in Ethiopia, forest administration policy has failed to address institutional problems that negatively affected national forest resources. The main institutional failure arose from restrictions on access and the rights of local resource users (Engida and Tashoma, 2012). Recently many other developing countries have become aware of this issue and taken measures to reform forest resource governance policies. One solution, PFM, was introduced to Ethiopia during the early 1990s by NGOs and international development organizations such as FARM AFRICA and GTZ (Gobeze et al., 2009).

The people of Ethiopia have longstanding indigenous institutions and a history of collective action for managing natural resources, as well as for dealing with socio–economic problems. These institutions have established rights, contributions, and benefit sharing mechanisms. Such informal institutions are categorized by the social purpose they evolved for. Moreover, traditional moral and ethical values of society are embedded within such institutions. The most widely practiced collective institutions in Ethiopia are *idir* and *iquob*. The main purpose of *idir* is to enable and support people who are burdened by funeral expenditures or other social obligations. The resources accumulated through these institutions, crops deposited after harvest, are used to insure members in the event of unexpected loss of property or household members and to help them cope up with food or financial shortages, disbursing these resources during periods of shortages or famine. *Iquob* is a voluntary cooperative savings association, typically composed of members with comparable earning capacity. *Iquob* differs from formal saving and credit mechanisms in two fundamental ways. First, *iquob* does not bear interest on the money saved. Second, *iquob* does not provide credit as money revolves. Important collective actions in Ethiopia are *jigie*/*debo* and *daddo*. Both refer to work or labour sharing groups, which may involve either human labour or draft animals such as oxen, or both. The only difference is that *jigie*/*debo* typically involves large groups of people from a particular village and *daddo* is practiced by relatively small groups (5-10) of households.

Other existing rural institutions that are useful for bridging the gap between formal and informal institutions are cooperatives and unions. In Ethiopia cooperatives and unions play major roles in mitigating institutional, governance, and market bottlenecks. Rural cooperatives are categorized on the basis of their underlying purposes: multipurpose agricultural, irrigation, forestry, consumer, recreation, cattle feed producing, grain marketing, dairy, apiculture, solar, and cooperatives for savings and credit. Cooperatives are often characterized by interrelated leadership between formal and informal governance systems at the local level (Spielman et al., 2008). Support for local micro-enterprises generates robust supply chains and networks for the diffusion of renewable energy, and helps build adequate local supply and demand, which is of great importance to rural society (IRENA, 2012f).

4.2. Bottlenecks and barriers to rural renewable energy use

Barriers to the use of renewable energy in developing countries are numerous, including: limited technical, structural, and regulatory capacity; a lack of incentives; market imperfections; and a lack of effective institutions and regulation. Studies have found that promoting adaptive R&D and supporting technological transfer can be especially valuable for developing countries as new markets emerge for renewable energy technologies (Popp, 2011). The main challenge is overcoming the initial capital costs, which are often too great for the rural poor relative to their financial capabilities and limited access to credit (IRENA, 2012f). The availability of microcredit is expected to expand market opportunities for up to 20–30% of rural residents in Ethiopia, and micro-leasing and fee-for-service arrangements could further expand this benefit to up to 70% of households, however, the remaining 30%-the poorest of the poor-may require fully subsidized services (IRENA, 2012g). The lack of existing energy infrastructure is another critical barrier. It is indisputable that limited energy infrastructure imposes a fundamental constraint on development in Africa (Ramachandran et al., 2009). From this perspective, Ethiopia's "greatest infrastructure challenge lies in the power sector, where a further 8,700 Megawatts of generation are needed over the next decade, which is four times the present national capacity, at an estimated annual cost of US$ 3.3 billion" (World Bank, 2010). Some of the most important barriers to renewable energy use are presented together with corresponding remedial measures in Table 4.3.

Table 4.3. Barriers to renewable energy use in Ethiopia and proposed policy measures to overcome them

Barriers	Remedial measures
Human capital	
Lack of technical expertise, skilled engineers Low human capital and a lack of technical capability Low investment in R&D, which is left to government	Linking indigenous innovators and entrepreneurs to global innovators Appropriate policies for building human capital, skills, and training opportunities
Market barriers and imperfections	
Structural rigidity, regulatory and institutional weaknesses Market fragmentation High transaction costs Poor physical infrastructure, limited information technology, high prices, etc.	Bridging demand-supply gaps Integrating dealers/suppliers to develop value chains and incentives Support the development of local value chains
Preferences and willingness to pay (WTP)	

Barriers	Remedial measures
Economic, social, physical, and environmental impoverishment Cultural preferences for biomass energy, traditional stoves, and thatched roofs Affordability and ability (prices, tastes, preferences)	Microcredit and subsidies for the poor 2-3% of households are able to pay for electricity (World Bank, 2008). Raising awareness Incentives such as capital subsidies and feed-in tariffs
Financial constraints	
Shortages of financial resources	Integration of microfinance, CDM, etc.
Institutional and governance limitations	
Institutional and governance weaknesses, particularly rural energy institutions Resulting technical capability and human skill limitations Ineffectiveness due to political ideology, bureaucratic torpor, rent seeking behaviour, or corrupt institutional cultures A lack of coordination among supply chain actors High transaction costs of renewable technology implementation	Preferential public policies Coordinated and coherent governance structure and institutional frameworks Appropriate governance and regulatory structures Conducive political system Improving the capacity, effectiveness, and transparency of governance entities Implementing decentralized energy schemes
Technological and technical capability limitations	
Energy inefficiency, particularly traditional biomass energy use Low levels of awareness A lack of technical capability for the application of renewable energy technology	Building technical capability in value chain development (production, transmission, transportation, processing, and end-use) Integration of technological innovation systems Broader use of improved efficiency biomass stoves
Infrastructural limitations	
Underdeveloped infrastructure	Decentralization and cost effective electrification
Information gaps	
Lack of information on available technologies, prices, etc. Knowledge gaps and lack of awareness of options	Raising awareness of energy options Providing basic education on available energy technologies

Three broad classifications or models of rural electricity suppliers are common in Ethiopia (Table 4.4). In Africa Kammen and Karibu (2008) found three actors in renewable energy delivery “concessions, cooperatives, and dealers.” In the concession model an entity or concessionaire is granted a franchise to supply power for profit, where the system functions either for the generation and/or distribution of energy. Cooperatives are membership-based commercial enterprises created to serve the interests of members. The role of dealers in rural energy supply includes selling and often maintaining equipment for the customers. Kammen and

Karibu also suggested government policies for rural electrification, including: “licensing, standards and guidelines, metering, tariffs, and output–based contracts.”

Unlike many private efforts, cooperative decision making may encounter free riding problems due to the heterogeneity of beneficiaries and prioritization of their individual interests. The advantage of cooperative resource use pertains to the ability to pool economic, social, and human resources for mutual gain. This requires knowledge-based integration of both formal and informal indigenous institutions that facilitates cooperative energy investment. Electricity supply in Ethiopia can be improved through different models or property right mechanisms illustrated in Table 4.4.

Table 4.4. Comparative descriptions of different power supply schemes

Description	Advantages	Disadvantages
Public investment		
Interconnected system (ICS) Self-contained system (SCS) EEPCO-a state monopoly UEA programmes	Scale of operation Public trust and goodwill	Inefficiency and bureaucracies Grid expansion costs ineffective for remote rural villages
Decentralized energy		
Cooperative decision making Cost and benefit sharing Collective property rights, appropriate incentives required Technologies include: smart-grid, micro-grid, small-scale hydroelectric, CSP, biogas, biomass gasification, other biomass power, and links with PFM, etc.	Economies of scale and efficient capacity utilization Inclusiveness Business opportunities Bargaining power Peer monitoring Ease of funding and security Improved credibility and sustainability	Stakeholder heterogeneity problems Free-riding problems Coordination failures may affect outcome Transaction costs Non-excludability
Independent investors		
Profit driven Appropriate incentives required Micro-scale technologies like private biogas digester, and solar PV	Complement to rural electrification Enhances competitiveness Enhances efficiency	May increase risk of monopolistic problems May increase risk and uncertainty
Household and small-scale renewable energy adoption	Improved management	Lack of upfront capital Low bargaining power Could be underutilized

4.3. Strategies and institutional arrangements for decentralized modern biomass energy use, participatory forest management, and climate change mitigation

4.3.1. Evolution of participatory forest management, energy, and climate change policies

Ethiopia's forest governance institutions have undergone three developmental phases of structural reform. During the imperial era (1930-1971) landlords were given absolute property rights over land and forest resources. The role of government was to collect taxes, but only a few landlords held the rights over the use of all natural resources. The majority of the peasants had to pay tribute to the landlords from their harvests in return for the rental value of the land they cultivated. This arrangement ultimately resulted in a wave of revolts by peasant tenants, university students, and others, which eventually brought down the imperial system. Subsequently the Derge regime assumed power based on the premise of bringing more equitable land and resource right distribution for the benefit of the peasant class. However, in keeping with its socialist ideology it brought forest property rights under the control of the state. This eventually yielded to the movement that brought the current governmental system into power in 1991.

The constitution of the current federal government recognizes property rights over land resources. No individual has the actual right to own land, but rather may acquire the exclusive right to use, lease, or conserve land based on a fixed-term contract. This essentially means that there are no clear property rights over communal forests. Concurrently, there have been three different forms of property rights over forest resources: private agroforestry plantations, state forests, and community forests. Private forestry is typically practiced on degraded parcels by individual farmers as a means of coping with the scarcity of forest resources, the prevention or mitigation of land degradation, income generation, and the provision of other benefits. State forests such as national parks belong to state or regional governments. Until recently communal forests were considered open access resources to all local people. As a result, these areas were often overgrazed, overexploited, and resources were depleted at an alarming rate. This situation has resulted in the drastic loss and degradation of forest resources and an unprecedented biomass resource deficit.

Under the new PFM approach the objective is to integrate conservation policies that simultaneously foster sustainable forest management and improve the livelihoods of those who are dependent on forest resources. Such policies are intended to restore degraded forests, encourage afforestation and reforestation on degraded land, and to improve the livelihoods of participating stakeholders. New strategies involve cooperative groups of households working together to conserve existing forests; plant trees on communal lands; preserve forest resources from encroachment by illegal loggers, livestock grazing, or other damages; and to sustainably harvest resources and share the resulting benefits (fuelwood, timber, non-timber forest products, livestock fodder, honey, etc.).

Two collective action activities related to energy use and forest management can be linked together to yield synergistic outcomes for improving livelihoods, and for achieving forest conservation and improved energy security. Figure 4.1 presents the main causal factors, policies, and envisioned outcomes associated with PFM for meeting energy needs. An important question that arises is: How can such policies be integrated into modern energy delivery? A critical issue here are the institutional and regulatory aspects. Such initiatives require complicated institutional, technical, coordination, and regulatory frameworks. Effective demand and supply management and evaluation of the effects on an intricate set of economic, social, and environmental issues also remain important issues. Forest conservation and community afforestation programmes are more likely to have broad positive impacts if they are linked to the development of sustainable biomass energy value chains. This could play a critical role in rural development, poverty alleviation, employment creation, energy security. The major drivers of forest loss are ineffective legal frameworks for the enforcement of property rights and forest protection laws, demographics, socio-economic conditions, market imbalances, and the persistence of obsolete energy use technologies. The most critical issues are discussed below.

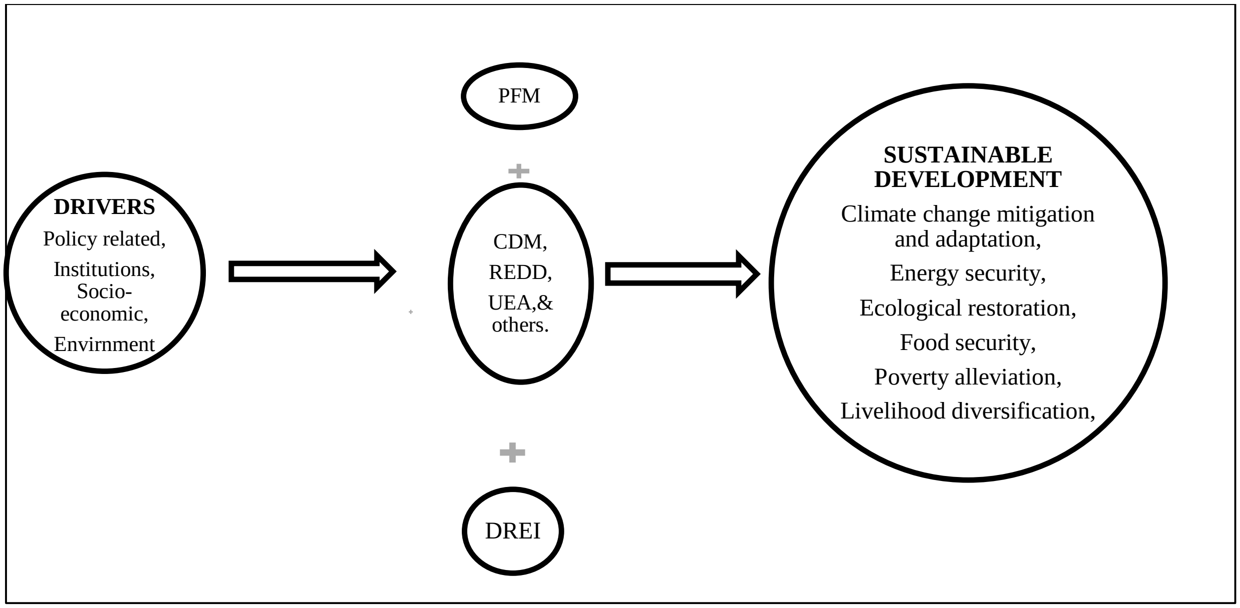

Figure 4.1. Sustainable forest management framework for clean energy development

4.3.2. Critical challenges and opportunities: climate change mitigation, agriculture, and biomass energy

There are a number of critical issues that need to be addressed in a way that is sustainable, innovative, and that mitigates poverty, socio-economic inequality, technical shortcomings, market imbalances, environmental problems, and the effects of climatic change. The triple dimensionality of sustainability (social, economic and environmental) and related public health considerations are often the main foci of mitigating rural energy problems in developing countries. The issue is complex as it is linked to agriculture, rural livelihoods, energy security, and emissions reduction. Emissions associated with biofuel life cycle production, extraction, transportation, processing, and consumption are also all valid concerns. Social aspects encompass important dimensions like gender equity, and inclusiveness of poor, marginalized, and minority groups. The majority of the poor in developing countries is directly dependent on natural resources. Both energy security and sustainable forest management institutions are important for improving their livelihoods.

Institutional problems are numerous, including state agencies that seek to retain control over resource management decisions, limited accountability of local institutions, and the lack of integration of institutional mechanisms and actors. Often this results in resource capture by local elites and weakens property rights over communal resources, which may worsen poverty and conflicts over resource. Government has a critical role in creating institutions that improve equitable sharing of the benefits and responsibilities of managing communal resources. It has been suggested that for successful implementation of PFM participants need to be defined in a more inclusive way, and that the divergent interests of heterogenous stakeholders need to be explicitly addressed (Kassa et al., 2009). These conditions are equally applicable to collective actions such as DREI initiatives. The sustainable development opportunities expected to be created by coordinating PFM and DREI may be immense. Success requires innovative strategies and institutions to be created and implemented to enforce collective agreement. Some of the critical opportunities and challenges to successful implementation of integrated PFM-DREI efforts are summarized in Table 4.5.

Table 4.5. Challenges and opportunities presented by community-based participatory forest management initiatives

Challenges	Opportunities
Attitude change: This requires simultaneous efforts to organize local forest resource users and other stakeholders and to facilitate a transition from traditional perspectives on resource use. **Land tenure security and land access**: The issue of land tenure security is vital to effective PFM. Forestry and agriculture compete for land. There are several factors that augment land scarcity including: rapidly growing population/declining per capita land area, large-scale commercial land leases, and the lack of secure tenure. Rural land management is often susceptible to corruption and regulatory and institutional problems due to reduced scrutiny of the behaviours of local administrators in remote areas. **Rules and regulations**: PFM is based on shared rights and responsibilities, and agreement regarding stakeholder responsibilities, and benefit sharing. This requires organizing people into cooperatives and partnerships or coordination among different actors (federal, regional, and local levels). **Heterogeneity**: Differences in wealth, religion, ethnicity, origin, etc., can hamper collective action due to divergent interests among stakeholders regarding their contributions and PFM benefit sharing. Competing and conflicting interests increase transaction costs, but this largely depends on the administrative capabilities with respect to conflict resolution and the degree of heterogeneity among stakeholders.	**Conservation**: Potential positive environmental benefits include: biodiversity and wildlife conservation, soil erosion prevention, and the provision of environmental services. Forests provide amenities as well as recreational and aesthetic benefits. Payments for ecosystem services (PES) for sustainable forestry efforts are one potential source of complementary income. **Carbon sequestration**: REDD and CDM are policies designed to link forestry activities with climate change mitigation efforts as CO_2 sinks. In addition to other livelihood benefits, income from carbon trading is a major incentive for sustainable forestry efforts in developing countries. **Clean energy**: Provided that appropriate technology is applied and sustainability assured, forest biomass produces clean energy that can substitute fossil fuels. Additional collective action is required to attain the capacity for advanced biomass processing and developing biomass value chains.

Challenges	Opportunities
Equitable cost-benefit sharing: The acceptable distribution of costs and benefits resulting from community forest conservation and sustainable forestry management is the primary management problem. **Inclusiveness**: In forming cooperatives, economically disadvantaged people whose livelihoods are highly dependent on forest resources may be excluded. This may fuel conflict over resource use unless inclusiveness of the poor and women is deliberate. **Transaction costs**: These arise during both cooperative formation and farther along the PFM process like in carbon trading, biomass marketing, etc. The reduction of transaction costs would increase participation among small-scale plantation owners (Smith, 2002). PFM and DREI require conflict resolution and negotiation mechanism on various issues that may increase transaction costs. **Inequality and equitability**: Economic inequality may obstruct PFM efforts. This is because differences in economic status and corresponding demand for forest products. Gender aspects are a critical issue because women are often excluded from participation and management of natural resource use agreements. **Biomass market development**: Markets for forest biomass products are currently underdeveloped in Ethiopia, which poses potential problems with respect to cost, prices, and related factors. **Governance and institutions**: It is necessary to establish effective mechanisms for project management and coordination of multiple stakeholders.	**Livelihood benefits**: Forests support the livelihoods of the marginalized poor of society in several important ways. Forests supply crucial food and livestock fodder resources, particularly in times of extreme drought and food shortages, thus contributing to food security. Foods that are directly provided from forests include: fruits, nuts, honey, game meat, and palm hearts or other vegetables. Indirect contributions arise from livestock that forage in forested areas. Rural households depend almost entirely on forest biomass for meeting energy needs. **Biomass value chains**: Forests provide raw materials for industrial processes such as the production of cosmetics, medicines, timber, fibre, and pulp pulp and fibre derived from woody biomass. Processing forest biomass into advanced energy products and other bio-based products can provide a basis for sustainable rural development. **Employment and business opportunities**: Forest biomass value chains have the potential to generate rural business and employment opportunities as well as added developmental benefits for local economies and forest communities. **Ancillary benefits**: Forest product and biomass value chains offer ancillary benefits such as opportunities to develop tourism, infrastructure, and institutional and market capabilities.

4.4. Lessons from case studies on participatory forest management

Forest governance institutions operate in Ethiopia at the regional scale. Currently there are many cooperative or PFM efforts in the country. Out of 58 identified Forest Priority Areas in Ethiopia, 37 (64%) are in Oromia (Terefe, 2002). There are already a number of PFM efforts underway in Oromia. Early pilot PFM projects include efforts in the Chilimo, Bonga, and Borana forests by a British NGO in partnership with a local NGO (SOS Sahel); another at Adaba Dodolla by GTZ; and one in the Belete Gera forest by the Japan International Cooperation Agency (JICA) (Terefe, 2002; Senbeta, 2006; Temesgen et al., 2007; Gobeze et al., 2009; Kassa et al., 2009; Tesfaye et al., 2011).

Chilimo forest: This project, collectively known as ‘the Chilimo Gaji Forest’ is situated 97 km west of Addis Ababa and 7 km north of a small town called Ginchi that is close to the main road to Ambo (Soromsa and Kelbessa, 2013). The forest is classified as a 'Dry Afro-montane Forest' and has an estimated area of 5,000 ha. The ethnicity majority in the area is the Oromo, and there are other ethnic groups that originally settled in the area to work in the lumber mills.

Agriculture is the backbone of the local economy, providing the basis of livelihoods for about 90% of the district's population (Gessese, 2009). That study also indicated that unchecked population growth and immigration pressure are the underlying reasons for forest loss in the area. Inhabitants of adjacent towns such as Ginchi and Welenkomi depend on biomass energy supplied by fuelwood collectors that operate illicitly. Favourable local climatic conditions for crop and livestock production also attracted immigrants from outside the district (Gessese, 2009). Unregulated fuelwood collection for household energy consumption is the primary local causes of deforestation (Mamo et al., 2007).

Different property rights schemes have been practiced to regulate the use of forest resources, including control by the state governments and foreign investors (Soromsa and Kelbessa, 2013). Since 1991 state control over the forest has weakened and deforestation has increased significantly despite being designated as one of the National Forest Priority Areas (Kassa et al., 2009). The forest supports local livelihoods in terms of environmental, social, economic, and cultural values. It also harbours endemic and other species that are economically and ecologically important (Soromsa and Kelbessa, 2013). There is also high demand for timber from the capital and many cities in central Ethiopia, giving the Chilimo PFM the proximity advantage of reduced transportation costs.

An innovative forest governance structure to integrate forest conservation with sustainable development was introduced in 1996 by the state government in Oromia in collaboration with FARM AFRICA and SOS Sahel (Kassa et al., 2009). The PFM framework was designed to facilitate partnerships among different actors (government, NGOs, affected communities and individual households) in order to conserve forest resources. The Chilimo PFM has helped resolve some of the existing conflicts that had arisen between government resource guards and members of surrounding communities who collect fuelwood and fodder as well as between native residents and more recent settlers (Kassa et al., 2009). Serious conflicts between PFM members and non–members have been avoided. Gessese (2007) calculated forest cover change in the district and found that forest cover had represented about 20% of the district in 1973, but only about 6% by 2000.

Bonga forest: The Bonga forest in the Kaffa Zone of the SNNP, about 430 km southwest of Addis Ababa. The Bonga forest is the origin of the coffee species *Coffea arabica*. The Bonga forest is also one of the two major broadleaf rainforest remnants in Ethiopia that are renowned for their rich biodiversity (Senbeta, 2006). The Bonga forest is part of the UNESCO Kaffa Biosphere Reserve. As a result the forest has received growing regional, national, and global attention. Various strategies have been implemented to address negative environmental trends.

The Bonga forest PFM was introduced with the objective of improving the livelihoods of forest dependent residents (Gobeze et al., 2009) and as an alternative forest management scheme to policing the forests using hired guards, which had been practiced for years to exclude local community members (FARM AFRICA, 2002 cited in Gobeze et al., 2009). The PFM effort has achieved positive forest conservation objectives and enhanced local livelihoods (Gobeze et al., 2009). This latter achievement was reflected in improved asset ownership or other household welfare indicators; however, overall income generation from the extraction of wood–based products has decreased significantly (ibid).

Bale highland forest: This forest is located in southeastern Ethiopia in the *woreda* of Dodola in the Bale Zone of Oromia, approximately 320 km from the capital. The Bale forest serves as a ‘buffer zone’ for the Bale Mountains National Park, which is home to endemic wildlife such as the endangered Ethiopian wolf (*Canis simensis*) and mountain Nyala (*Tragelaphus buxtoni*). Although open-canopy forest cover did not show any significant changes in area the amount of dense-canopy forest has been depleted at an alarming rate (Mideksa, 2009).

The Bale highland forest PFM is jointly implemented by the regional government of Oromia (Bale Forest Enterprise) in partnership with the NGOs FARM AFRICA and SOS Sahel Ethiopia (Teshoma, 2010). This effort was started as a pilot project with the overall goal of organizing the local community into a ‘Forest Dwellers Association,’ known by its acronym in the local language as WAJIB (*Waldaa Jiraatotaa Bosonaa*), the members of which are required to protect the forest, perform management activities, and pay annual forest rent in return for the right to live in the forest, extract forest–based products, and graze livestock in the forest (Terefe, 2002; Tesfaye et al., 2011). Establishment of the integrated forest management project in the area resulted in lower rates of forest cover loss during the 2000–2005 period relative to the 1986-2000 period (Gessese, 2009). According to Mideksa (2009) forest cover in the area declined from about 28% to only 16% over the 1986–2005 period. The lack of appropriate institutions and governance mechanisms has contributed to the high deforestation rates.

4.5. Lessons for decentralized renewable energy investment

Decentralized energy generation and distribution is considered a promising mechanism for supplying clean energy to remote rural communities. Decentralized renewable energy systems may ease financial constraints and can be large enough to reach economies of scale that keep distribution and transmission costs sufficiently low to offer a competitive advantage over national grid delivered electricity. Developing such systems in rural areas may also benefit from transport cost reduction advantages due to the close proximity to biomass feedstock sources. Decentralized systems also reduce energy losses associated with distribution, transmission, and transportation.

There are many hybrid renewable energy technologies for harnessing available renewable energy resources that are applicable to decentralized systems. In Nepal a programme known as the Rural Energy Development Programme was initiated in 1996 as a decentralized approach for providing energy to approximately one million people (UNDP, 2011). The scheme has not only strengthened local governance, but has also contributed to the reduction of IAP and supported the development of rural economies and livelihoods by providing reliable, low-cost electricity to rural communities. There are two existing examples of decentralized energy development in

Ethiopia: institutional biogas (Tadesse, 2010) and community–based jatropha cultivation for biofuel on degraded communal land in Bati, in the Oromia Zone of Amhara (Amsalu et al., 2013).

4.5.1. Insights from focus group discussions

Focus group discussions were held with key actors in three communities: Udee and Trirufe in Oromia, and Addado in SNNP. The objectives of the discussions were to identify bottlenecks, energy access problems requiring policy intervention measures, challenges, and opportunities for establishing and operating DREIs. The discussion participants included representative farmers (both men and women), cooperative management committees, local *kebele* administrators, women's group representatives, agricultural extension technicians, biogas digester owners (in Udee), health extension technicians, and teachers. In each of the villages a half–day, in–depth discussion was conducted with the participants. Discussion topics included the technical, economic, and problems related to existing biomass energy utilization, local energy availability and performance, problems with private biogas digesters, improved efficiency cooking stove designs and use, forest conservation, and the viability of DREIs.

Discussion participants indicated that existing institutions like *idir* and *iquob* only address specific purposes and have meagre resources, and thus were insufficient for supporting DREI efforts. In general, discussion participants indicated that collective action for developing and maintaining biomass energy would be difficult. The perceived barriers included:

- the lack of local management and operational capacity,
- the potential for free-riding problems,
- the lack of incentives,
- local socio-economic heterogeneity,
- poverty (the lack of financial support for a DREI project)

Improved efficiency biomass stoves: According to the discussion participants improved efficiency cooking stoves are affordable to local households. Participants also indicated that limited stove availability, limited awareness about the stoves, and the local scarcity of required stove production inputs and maintenance were challenges to more widespread use. In Addado there was no available promoter of improved stoves and almost none of the households were familiar with them. Discussion participants expressed that this was also partly due to the limited media available for promoting the stoves such as television or radio broadcasting.

Another limitation identified was the lack of an organized initiative or incentives. As described by the discussion participants, poor people are more likely to adopt new technologies based on positive experiences of peers or others around them, which has limited broader adoption of the improved stoves. Discussion participants asserted that peasants typically have subdued levels of responsiveness, risk taking behaviour, and learning capability. Participants agreed that local decentralized production of improved stoves would be beneficial provided there was adequate support from the government such as technical training for cooperatives and assistance for acquiring necessary manufacturing inputs. Broader production and dissemination of improved efficiency cook stoves may be the most cost effective means of improving biomass energy use efficiency in Ethiopia.

Ethiopian energy policy clearly emphasizes biomass energy use efficiency improvement. The current GTP includes plans to produce and disseminate approximately nine million improved efficiency stoves by 2015 (CRGE, 2011). The stoves are to be manufactured using locally available inputs, which will help create local business and employment opportunities.

Focus group discussion results suggest that a decentralized approach to the promotion of improved efficiency stoves in Ethiopia may offer multiple advantages over traditional approaches with regard to the establishment of sustainable improved efficiency stove supply chains. This would help build capacity and confidence among those who adopt improved stoves, improve the dissemination of information, assure local availability of stove components and maintenance and repair capabilities, as well as cultivate social networks for learning and innovation. An innovative decentralized approach to the production and dissemination of improved stoves may help to scale up and speed the pace of their adoption. The benefits of a decentralized approach arise from:

- increased consumer confidence;
- greater ease of capacity building, promotion, and technical training;
- generation of local business opportunities;
- improved local access to maintenance and repair services;
- facilitation of incorporating feedback into product design and modification, which would likely increase demand;
- the opportunity to reach economies of scale; and
- increasing local employment opportunities.

In Ethiopia and other developing countries people often purchase goods in local markets where product guarantees are not available. A decentralized approach, however, helps address such problems by increasing customer confidence. Since production is in closer proximity to the consumers, transaction costs are reduced and there is greater quality of control and management.

Biogas: The objective of the focus group discussion with biogas digester owners in Udee was to identify the technical, economic, social, and other factors that limit biogas performance. Participants identified many benefits of biogas digesters like the production of compost used as organic fertilizer, efficient use of time, the lack of a gender equity issue in the operation of digesters, cleanliness, etc. The participants also identified drawbacks such as:

- the limited applications of biogas produced by digesters due to the lack of appropriate stoves;
- the low amount of energy delivered, which is suitable for light cooking or illumination needs, but inadequate for baking the traditional staple *enjera*;
- the general lack of knowledge about biogas;
- the lack of technical training and orientation;
- high installation costs;
- resource constraints (water) for daily biogas plant operation;

- the need for a minimum of four head of cattle to generate quantity of the manure required to operate the biogas digesters;
- the lack of support from the government for biogas technology application; and
- the lack of technical support and follow up by an appropriate institution.

When asked about the feasibility of a local decentralized neighbourhood or village scale biogas digester system, participants expressed concerns regarding the potential for 'free-riders' due to the high labour requirements of daily operations. But they also reflected on the benefits of biogas, including clean energy and compost for improving soil fertility. They identified obstacles to be overcome and ways that the government could intervene more proactively.

Solar cooperatives: Discussion participants considered solar power to be a more plausible option for decentralized energy generation than biogas. Discussion participants indicated that there were existing government efforts to develop DREIs based on solar cooperatives. The government of Oromia organized solar cooperatives whose members provide about 5% of the upfront capital costs and the remaining 95% is covered through microfinance credit. Some cooperatives had already provided the required 5% but expressed their dissatisfaction with the slow rate of response by the government.

4.5.2. Lessons from institutional biogas experiences

Private and decentralized biogas systems were compared using a cost benefit analysis of the household choice of investing in either option. In Ethiopia biogas power systems have already been used by institutions such as schools, health centres, religious facilities, hotels, prisons, farms, and orphanages (Tadesse, 2010). These experiences provide policy lessons about similar neighbourhood DREI biogas efforts. The required size of such biogas plants would vary depending on the number of participating households and on technical and economic feasibility issues.

Cost estimates: Tadese (2010) studied institutional biogas systems that were installed in different regions of Ethiopia over the period from 1974 to 2001. There were a total of 91 institutional biogas plants built among Amhara, Addis Ababa, Oromia, SNNP, and Harari. The construction costs of biogas digesters depend on the volume of the unit and the availability of construction materials (i.e. stoves, pipes, and other accessories). The average institutional biogas digester installation cost was estimated from Tadesse (2010) and is presented in Figure 4.2. Private biogas digester installation costs were based on information from the national biogas project.[17] The optimal number of households participating in a DREI biogas scheme was determined from the institutional biogas information discussed above.[18] The net benefit

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[17] The NBPE was founded by ERDPC and SNV. It subsidizes about 33.33% of the cost of installing biogas digesters. According to NBPE the cost of each 6 m^3 biogas digester was about 11,000 ETB (US$ 596) in 2011.

[18] This was based on the assumption that each household would have a share equivalent to a 6 m^3 digester (i.e. the size of the plant divided by 6 m^3 to determine the number of households that can participate). Then the total cost was divided by the number of participating households in each of the institutional biogas systems and the mean cost per household.

predictions were based only on installation costs, which were highly variable. The mean cost of institutional biogas systems was about US$ 502.7 for 6 m^3 of capacity, which was used for the cost–benefit analysis.

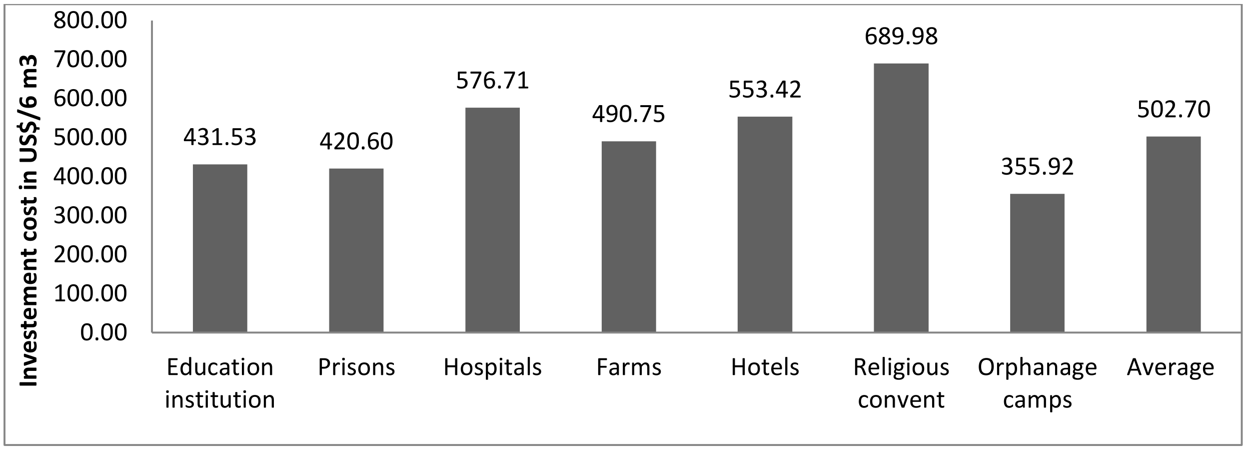

Figure 4.2. Mean installation costs of institutional biogas digesters in Ethiopia

Source: Based on Tadesse (2010)[19]

Benefit estimates: Biogas offers tremendous potential sustainable development benefits. Biogas requires less household labour time than traditional biomass energy use. Biogas digesters also supply organic fertilizer. The estimated opportunity cost of household biomass energy collection[20] presented in Chapter Two was used to estimate benefit from labour time save. The shadow opportunity cost of time saved was computed by multiplying the amount of time needed to collect fuelwood and cattle dung with the mean shadow wage from the statistical summary presented in Chapter Two (Table 2.6). Second, the direct household expenditures on energy[21] from the household survey data were computed. Third, the shadow value of solid biomass was computed using mean annual household biomass energy use presented in Table 2.15 in Chapter Two and the shadow value of solid biomass from energy sector model presented in Chapter Three presented in Figure 3.17. That cost excludes labour costs only and only accounts for the land opportunity cost of biomass production.

Table 4.6. Estimated household expenditures on energy in Ethiopia (US$)

Variables	Fuelwood	Agricutural fuels	Energy expenditures	Total
Biomass collection time in hours	489.00	126.00		615.00
Shadow wage (US$/hour)	0.10	0.10		
Labour cost (US$/year)	48.90	12.56		61.46
Energy expenditures (US$/year)			13.42	13.42
Shadow value of biomass (US$/kg)[22]	0.02	0.02		

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[19] The investment cost was adjusted for inflation taking 2005 as the base year. Tadesse (2010) found that most of the institutional biogas digesters (65%) were constructed during 1995-2000 or 2003-2008.

[20] The amount of biomass energy consumed annually was multiplied by the respective shadow wages (presented in Chapter Two).

[21] Household energy expenditures on biomass, candles, kerosene, and electricity were derived from the survey data described in Chapter Two.

[22] The shadow value of solid biomass was computed from the energy sector model presented in Chapter Three at about US$ 18 per tonne.

Variables	Fuelwood	Agricutural fuels	Energy expenditures	Total
Amount of biomass conserved (kg/year)	1959.85	85.78		2045.63
Value of biomass conserved (US$/year)	39.20	1.72		40.91
Total benefit (US$/year)	88.10	14.28	13.42	**115.80**

The mathematical formula of the benefit function was expressed as:

$$TB_t = w_i L_{it} + P_i q_{it} + E_t \tag{4.1}$$

where, w_i represents the shadow wage, L_{it} is the amount of labour time in hours per year required for biomass production, q_{it} is the quantity of biomass replaced by biogas, and E_t represents annual expenditures on energy saved as a result of biogas use. Then, the present benefit was calculated as:

$$PB = \sum_{t=1}^{T} \frac{TB_t}{(1+r)^t} \tag{4.2}$$

where PB represents the discounted present benefit, T is biogas plant life, and r is the interest rate. The net present benefit was specified as:

$$NB_s = PB - C_s \tag{4.3}$$

where NB_s represents the net present benefit of the biogas scheme, and C_s represents the corresponding capital investment cost. If a household receives subsidy support (P_s) the the net benefit is given as:

$$NB_s = PB - C_s + P_s \tag{4.4}$$

The analysis has a specific limitation that needs greater study. There were costs and benefits that were not included in the analysis. Some of the information was not available and some variables are not easily measurable. There was a lack of information on compost production and its costs. Environmental benefits of clean energy such as reduced IAP, deforestation, environmental degradation, and increased carbon sequestration benefits of conserved forests, in addition to other livelihood benefits and the reduction of externalities should be incorporated into the analysis but unfortunately are very difficult to quantify. There was also no information available on the operation and management costs of biogas digesters. These costs include the water and dung fed to the digesters, maintenance, and repairs. The only cost considered was the construction cost, which is a main constraint to biogas adoption in rural Ethiopia. Investment in decentralized biogas systems may also involve significant transaction costs that were not possible to include due to lack of the data. Although these conditions may introduce some bias the analysis results offer important insight for future research efforts and rural energy policy design. Gwavuya et al. (2012) studied the costs and benefits of biogas in Ethiopia on the basis of household survey data. They considered cost details and benefits of 4 m^3 and 6 m^3 digesters and different household groups according to energy behaviour: fuelwood purchasers, fuelwood collectors, and cattle dung collectors. Their results indicated that biogas digesters yielded positive net present values for the different households, both with and without subsidies, which is consistent with the results of this study (see Figure 4.3). Gwavuya et al. did not compare cost advantages of decentralized versus private biogas digesters.

The empirical results for different biogas systems and digester longevity periods, both with and without subsidies, are described in Figure 4.3. The up-front capital costs were fixed as computed above, but the net benefits were discounted to present value. The predicted benefits come over time, but installation costs are only incurred initially. Amortization periods varied significantly. A private biogas digester without subsidy would require an approximately seven year amortization period to cover the installation costs. Decentralized biogas digesters without subsidy would require about five years to recover installation costs. A subsidized private biogas digester would require an amortization period of about three years and decentralized biogas without subsidy would require about four years.

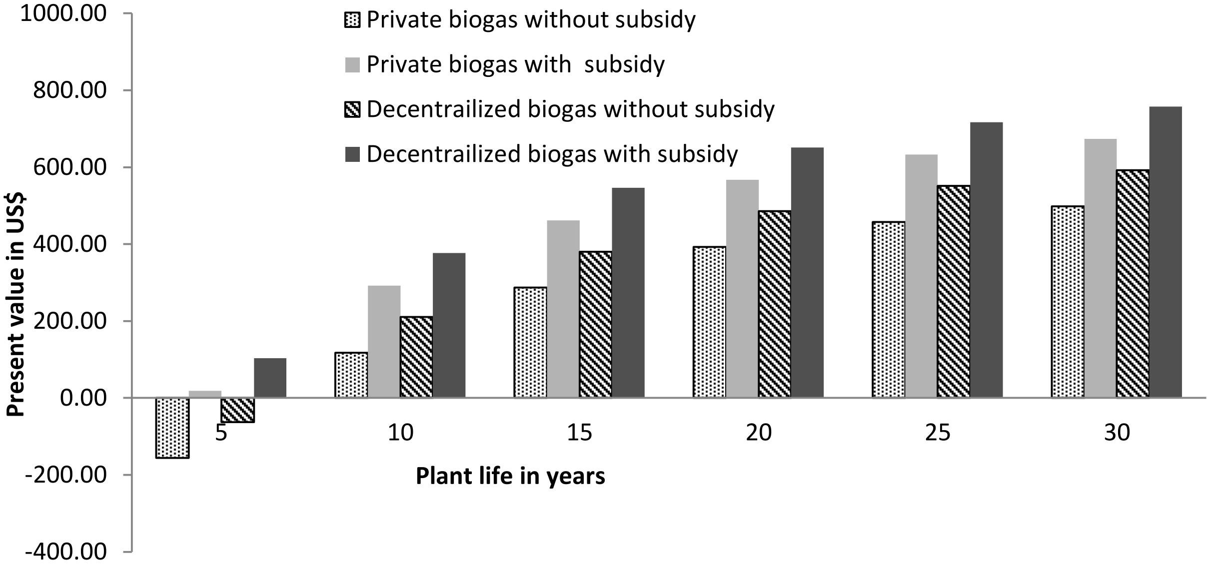

Figure 4.3. Estimated household net economic benefits of private and decentralized biogas systems[23]

The highest predicted gain was for subsidized collective biogas digesters. Collective biogas digesters offer many opportunities such as reduced financial burden and meeting NBPE support requirements such as owning a minimum of four cattle. Households must be willing to collaborate and establish acceptable incentives for households with more cattle to compensate for those with fewer cattle. Formal and informal institutions, legal frameworks, and supporting policies can all play substantial roles in reducing the transaction costs.

The results indicate that providing subsidies for decentralized biogas digesters could generate greater benefits. When a digester lifespan of 20 years was assumed, subsidized systems were predicted to have a net present value of about US$ 652 followed by unsubsidized private digesters that would have a net present value of about US$ 567. Unsubsidized collective digesters would have a net present value of about US$ 486, while unsubsidized private digesters would be US$ 392.

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[23] An interest rate of 10% was assumed for computing the present benefit value.

4.6. Supply and demand of decentralized bio–based energy and other renewable energy sources

4.6.1. Biomass supply

Biomass resources are supplied from the agricultural and forestry sectors. Bio-refineries could be located near each of the national priority forest areas, which are already under PFM schemes. Households are expected to gain a broad spectrum of livelihood benefits from participating in PFM efforts and power generation from local bio-refineries. Positive impacts of PFM on both forest condition and the living conditions of participating households have been documented (Gobeze et al., 2009). For example, households in the Bale forest reported that income from forest products represented about 34% of their total annual income (Tesfaye et al., 2011), while a study in Chilimo forest found that the share of household forest-based income was about 39% (Mamo et al., 2007). The two studies indicated that income from fuelwood collection represented the dominant share (55%) of forest-based income in Bale and in Chilimo (59%). Kassa et al. (2009) also evaluated the circumstances in Chilimo and predicted that without PFM the resource base would have become severely degraded in less than ten years and that PFM represents a win-win scenario for the forest and its inhabitants. The rural energy market is primitive and poorly organized resulting in high transaction costs, particularly in biomass energy trade. The financial benefits from PFM include revenues generated from timber, biomass energy sales, sport hunting, PES, climate change mitigation forest conservation incentives (REDD and REDD$^+$), and the carbon-financing fund (CDM). Benefit sharing mechanisms require consensus on stakeholder roles and responsibilities.

The integration of PFM efforts into decentralized modern biomass energy value chains would be expected to improve local livelihoods, forest conditions, the sustainability of forest management, and the availability of energy in rural areas. Optimally biomass would be used competitively on the basis of expected returns contributing to improvement in resource use efficiency. A decentralized strategy could also be effective for liquid biofuel (ethanol and biodiesel) systems and offers many developmental opportunities. A study of the Bati community-scale jatropha biofuel project in found that it has improved the livelihoods of participating farmers, helped rehabilitate degraded land, improved watershed management, stimulated rural development, and improved energy security (Amsalu et al., 2013). Those researchers also found that low yields, poor market linkages, and the lack of financial and technical support remain serious constraints. Supportive policy incentives could facilitate the implementation of larger scale efforts in other communities.

Bio–refineries: Bio-refineries processing biomass resources into clean energy in liquid form (bio–ethanol, biodiesel), heat, or electricity. Decentralized biomass electrical power, biomass gasification, and cogeneration projects offer promising opportunities for improving rural energy access. Developed countries have established power generation projects based on these technologies. Developing countries like Ethiopia have an opportunity to adapt these technologies to local conditions and apply them in order to develop human capital and improve living standards. Bio-refineries for biomass densification and charcoal briquettes have already emerged in Ethiopia, although these efforts are limited to major cities. Similar systems can be effectively implemented as decentralized systems at smaller scales for rural communities. Biomass gasification is another important technology that can be plausibly applied for rural electrification efforts.

Microcredits: Financing renewable energy development is a formidable obstacle. Ethiopia has well–established micro-finance institutions in both urban and rural communities. These provide group based loans that can be applied towards infrastructure development or in this case decentralized energy generation systems. The microcredit concept could also be systematically integrated innovatively into adapted forms of the traditional informal institutions (*iquob* and *idir*), cooperatives, and unions.

Business: Decentralized energy not only generates clean energy, but also creates business opportunities provided that suitable government policies are implemented. Typically energy produced by decentralized systems is intended to supply specific groups of households or communities. Surplus energy could be sold to non-members within or in nearby communities. If conditions are favourable energy could also be supplied to other regions or to larger grid systems. Refined biomass products such as charcoal briquettes, wood pellets, and liquid transportation fuels may be conveniently transported or exported. This would generate revenue streams that can help repay debt acquired from project establishment, be reinvested, or simply provide income to participants. In addition to energy there is also a huge demand for pharmaceutical materials as the country is dependent on imports to meet most demand. This situation offers an important opportunity to develop pharmaceutical bio–refineries that use biomass and chemicals that could boost local businesses, reduce dependency on foreign sources, and potentially supply global markets. In Bangladesh Chakrabarty et al. (2013) found that biogas reduced time spent on cooking to the point that women were able to dedicate themselves to income generating jobs.

International organizations: Almost all of the PFM projects in Ethiopia are supported by NGOs. These organizations operate in critical roles such as fund raising, capacity building, facilitating knowledge transfer, providing technical training and orientation, facilitating communications and dissemination, and raising awareness. There are various funding opportunities for clean energy in Ethiopia, such as the World Bank rural electrification fund, government subsidies, and the recent ‘President Obama’s Africa Power Initiative.’ Ethiopia is also a carbon trading hotspot, offering opportunities for incentive based conservation.

Financial incentives for forest conservation and clean energy development such as REDD, REDD^+ readiness, and CDM could be effectively coordinated to facilitate collective action. The Ethiopian government has incorporated the national REDD^+ readiness efforts into a comprehensive Climate Resilience Green Economy (CRGE) strategy. Another key project related to financing clean energy access in rural Ethiopia is the UEAP. This underpins the impetus of an integrated incentive strategy for climatic change mitigation, livelihood improvement, environmental restoration, and clean energy access.

4.6.2. Energy end users or consumers

Decentralized energy is not only for communities or groups of participating households. Such efforts can also be used to supply institutions, be traded outside of the participating households or communities, or used domestically. Though this discussion has focused only on energy generation, it is important to recognize the potential applications for chemical and material production for healthcare, education, and wood pulp industries.

Rural institutions, agricultural industries: Rural institutions in Ethiopia that would benefit from greater access to electricity include: schools, health centres, *kebele* administrative offices, mills, shopping centres, and many other rural enterprises. Energy is also used for pumping drinking or irrigation water, access to which is often another critical problem in rural communities. Clean energy, particularly electricity, can have a critical role in promoting rural education. In order to read at night in rural areas students usually use relatively dirty technologies such as kerosene lanterns or candles, which and are not only poorly suited for educational illumination needs, but can present health risks and fire hazards. Furthermore, there are no night schools in rural areas because of the lack of the means to illuminate suitable facilities. Most farmers who could benefit from additional education cannot attend school during the daytime because they must work on their farms. Decentralized energy has an important role in the development of human capital, which is crucial for rural transformation, improving food security, and public welfare. Health centres, both human and veterinary, require electricity for various purposes such as refrigeration of medicines, computers and office or laboratory equipment operation, and illumination. Electricity demand is high among rural institutions such as mills, market centres, churches, and mosques.

The lack of access to modern energy is a major constraint for agricultural industries, with most businesses requiring privately owned diesel generators. This gives decentralized renewable power systems a competitive edge for supplying clean energy to dairy, food processing, leather industries, etc. There are also craft industries like black smiths that traditionally use charcoal to heat iron that would be able to use cleaner energy substitutes supplied from the decentralized schemes.

Households, communities, and regional trade: DREI participants can engage in all stages along the energy generation and distribution process as biomass suppliers, investors, operators, consumers, and energy sellers. Biomass energy offers more tradable forms of energy for developing countries as households in urban areas often depend on biomass energy from rural sources. The markets for biomass are typically poorly organized and inefficient, reducing their economic potential by raising transaction costs. Decentralized generation and distribution of cleaner and more modern forms of energy to urban consumers offers several advantages:

- there are a variety of products that can be easily transported,
- transactions are reduced,
- the linkages between urban and rural economies are strengthened,
- urban households would benefit from cleaner forms of biomass energy, and
- improving regional integration for realizing both economic and political domestic benefits.

As indicated in Chapter Three, biomass production and power generation have different shadow values that vary by region. Decentralized biomass production should increase the availability of products that can be easily traded and transported provided that efforts are well regulated and that multiple sustainability criteria are met.

Transportation and industrial sectors: Ethiopia has a policy mandate to increase the share of biofuel in blended diesel. Decentralized generation of biodiesel and ethanol could be utilized for transportation fuels. Surplus electricity can be fed into grid systems, depending on the source's location relative to grid infrastructure. The industrial sector energy demands include electricity, biomass for heating, and wood pellets.

Agriculture: Agriculture can be a key part of decentralized biomass energy production as both a biomass feedstock supplier and energy consumer. Agriculture requires energy for various purposes such as pumping irrigation water, powering tractors and other motorized equipment, and processing and transporting harvested goods. Agricultural intensification, the application of different technologies, and the delivery of extension services all require energy.

Energy exports: Processed biomass energy can be appropriate for trade. Forms such as wood pellets, energy crops, and processed biofuels can be practically transported and even exported. Typically, households in participating communities supply biomass feedstock individually or as members of bio-refinery cooperatives, and as energy consumers.

4.7. Legal framework, institutions, and the role of government

Like most other developing countries, institutional settings, legal frameworks, and strategies for clean energy development in rural areas are underdeveloped in Ethiopia. Institutional obstacles exist for both forest governance and clean energy supply. The root cause of this problem is the lack of appropriate forest governance institutional structures and policies that address energy deficiency. From this perspective, the government has the potential to have a crucial role in establishing the necessary institutional and legal framework for enabling effective linkages among sustainable energy resource use, community-based forestry, and conservation activities.

Decentralized energy production and use at smaller geographic scales requires appropriate regulatory framework and institutional structures. The administrative structures at different geo-political levels could be coordinated effectively with respect to channelling technical and orientation assistance, as well as for offering incentives. At the national scale the EREDPC works in collaboration with international organizations to support rural energy supply. Supportive legal, regulatory, and institutional systems can be designed, implemented, scaled-up, and effectively linked with forest conservation programmes through appropriate policy.

Improving the sustainability of energy generation systems would require knowledge-based integration of informal and formal institutions, different federal and regional-level entities, and international donor organizations. To integrate PFM and renewable energy technology at regional scales would require coordination through the federal government and regional-level entities. Relevant federal and civil society entities include: the Ethiopia Environmental Protection Authority (EEPA), the MoWE, EREDPC, the EEA, the Ministry of Agriculture

(MoA), EEPCO, regional energy agencies, universities and other education institutions, research and development institutions, federal and regional cooperative agencies at different levels, and microfinance institutions.

Regional institutions have key roles in forest conservation at different scales. The Oromia Forest and Wildlife Enterprise (OFME) is responsible for forest management in Oromia together with other supporting institutions such as the Oromia Cooperative Promotion Agency (OCPA), which helps organize communities into cooperatives and unions, and to formalize land use rights. At the heart of the CRGE strategy are the sustainable management of forest resources and a clean energy technology agenda. Recently the government of Norway initiated the BioCarbon Fund in Ethiopia in partnership with the World Bank to help finance REDD$^+$ readiness measures in support of the CRGE (World Bank, 2013d).

Legal and community-level regulatory enforcement systems also have crucial roles in enforcing compliance. Such systems can be adapted to the objective of supporting sustainable forest conservation, reducing carbon emissions, and financing DREI for rural communities. Energy pricing policies could be established in a manner that supports cooperative-based rural energy producers, users, and distributors. Recently, the Ethiopian Energy Agency (EEA) replaced the Ethiopian Electricity Agency as the government entity responsible for regulating private investment in the energy sector. This agency is also expected to set prices for private and state power distributors.

Supply chain development requires strong ‘public–private partnerships’, which are particularly relevant to a decentralized energy approach. This can include supporting microenterprises through building their capacity for energy investment. Governments can facilitate access to micro-credit for energy producers and implement effective subsidy schemes to help enable poor people to participate in DREI efforts. Such a strategy is consistent with the UN sustainable energy projects, the World Bank UEAP, CDM and other incentives. A principal challenge to the sustainability of PFM efforts in Ethiopia is limited government support (Gobeze et al., 2009). As a result, rural energy institutions are also underdeveloped and lack effectives in coordinating, governing and implementing national policies with decentralized projects.

There are various strategic policy options for implementing agricultural and forestry sector initiatives to improve the sustainability of biomass exploitation. Such efforts should be aligned with a sorely needed agricultural transformation in Africa, not least of all for Ethiopia. Some of these changes include: improved agricultural technologies for livestock and crop production, family planning through health services, bridging knowledge gaps, facilitating the local production and distribution of improved efficiency cook stoves, supplying communities with appropriate renewable energy technology, more sustainable use of forest resources, and greater reforestation and afforestation efforts. Existing efforts could be scaled up, sustained, and harmonized into the CRGE strategy and transformed into modern energy value chains.

4.8. Conclusion and recommendations

Supplying clean energy to remote areas through the expansion of existing grid systems is not cost effective in Ethiopia, and furthermore would be technically difficult and impractical. The study results suggest that government intervention in rural energy and attention to decentralized approaches are necessary to close the energy supply and demand gaps in rural areas. Rural communities are typically suited for improved renewable biomass resource use, small-scale hydroelectric projects, concentrated solar power (CSP), solar PV, wind, or any hybrid system that contributes to energy security and enhanced livelihoods. The development of a green economy could help reduce carbon emissions and create competitive resource advantages. Various technical, demographic, economic, social, institutional, environmental, and market barriers have inhibited clean energy development in Ethiopia. In this arena, DREI appropriate technologies, particularly bio-based technologies and solar power, have attracted considerable support in recent years. Biomass energy has the potential to be used for decentralized rural energy supply, as it is already the predominant energy source for rural residents. Bio–refineries can deliver clean energy not only for participating households, but also to communities and outside areas, rural institutions, or feed surplus energy into larger grid systems depending on the location of plants and other considerations. The government could help build effective institutions, legal frameworks, and regulatory structures that support decentralized energy use and forest conservation to help overcome the technical, economic, institutional, and financial barriers to renewable energy development.

Chapter Five

Summary, conclusion and policy recommendations

5.1 Summary and conclusion

The quest for safe and secure sources of food, energy, water, health services, and other livelihood needs has become and will continue to be major challenge, particularly in Africa and specifically Ethiopia, where food and energy security are already daunting challenges. Energy is fundamental to food production and sustainable long-term economic and social development. The nexus of water, energy, and food requirements is further complicated in Ethiopia, where people and the economy are highly dependent on agriculture and there is a high frequency of drought that is likely to be exacerbated by a global climate change.

Ethiopia is among the few countries with a broad diversity of abundant renewable energy resources. Paradoxically, the country suffers acute deficits in terms of access to clean energy. In combination with the steady, substantial drop in the costs of other renewable energy technologies like wind turbines and solar panels, renewable energy sources offer many opportunities. Ironically only a minor fraction of these resources has been exploited so far. National statistics indicate that the potential of biomass energy is actually being exploited, representing approximately 50% of the woody biomass potential and 30% of agricultural residues, but only 5% of hydroelectric potential and less than 1% of combined wind, solar, and geothermal potential is currently exploited. The country has also experienced unprecedented growth in demand for electricity. The severe energy crisis in the country is reflected in the low level of access to clean energy in remote rural villages, where over 85% of the country's impoverished population resides. Alleviating the energy crisis by harnessing these renewable resource opportunities offers long-term societal and economic development benefits.

This research focused on rural household bio-based energy utilization behaviour and its linkages with livelihoods and food security. The study has three main foci. First, labour allocation among fuelwood collection, agricultural production and off-farm employment was estimated and its drivers in Ethiopia were examine in order to better understand the trade-offs between fuelwood collection and food production, and related welfare effects of fuelwood scarcity. Due to the complicated linkages between fuelwood collection and agriculture, the impacts of fuelwood scarcity on the livelihoods of households that rely on fuelwood for subsistence purposes, especially the impacts on labour allocation, are undetermined. These linkages were empirically investigated to reveal the welfare implications of changes in the shadow wages of labour on household labour allocation, both separately for each activity and jointly using a panel data analysis approach. A FE-2SLS model was employed to conduct an empirical examination of competition for household labour based on different livelihood strategies using panel data. Moreover, SUR and AIDS models were applied to estimate the joint annual hourly labour allocation and labour share among the three activities respectively.

The effects of fuelwood scarcity were examined by investigating the relationships among wages and labour allocation. The findings indicate that labour allocated to fuelwood collection was expected to decline with increases in agricultural wage, but that agricultural labour was positively related to fuelwood wage, both of which were consistent with the original research hypotheses. The results indicate trade-offs between fuelwood collection and food production from a labour allocation perspective. The effects of fuelwood scarcity were examined through the direct impacts of fuelwood shadow wages on agricultural and fuelwood collection labour time. Changes in forest access that increase fuelwood shadow wages by 1% were predicted to lead to an increase in agricultural labour allocation of 2.62%. This indicates a fuel-food trade-off, as increases in fuelwood scarcity reduce the fuelwood shadow wage with a negative effect on labour available for food production.

The second econometric model was used to investigate the effect of shadow wages on household energy and food expenditure patterns and fuel choices or fuel use composition using panel data econometrics. The results suggest that increases in fuel shadow wage reduce per capita expenditures on fuelwood and charcoal, but that increases in off-farm wages resulted in increased per capita kerosene expenditures. The shadow wages of fuelwood collection, agriculture activities, and off-farm employment resulted in the expected increases in the likelihood of households choosing to purchase of modern energy options relative to biomass energy sources. The results indicate that household access to relatively lucrative off-farm employment opportunities that improve labour productivity has important implications for conserving and restoring forest resources. The model results were consistent with previous studies across the developing world.

Lastly, the econometric analysis focused on household bio-based energy utilization and energy substitution, its determinants, and related welfare effects. The results of the econometric analysis revealed the consistent influence of important explanatory variables. The predicted shadow prices were used along with other variables. Both fuelwood and agricultural fuel use were negatively associated with their own shadow price, but only the former was statistically significant. This suggests that fuelwood scarcity induced households to reduce its use. The cross-price elasticity values suggest that there is no substitutability between fuelwood and agricultural fuels, but that the latter are used as a backup for the former, which conforms to the findings of previous studies from Ethiopia and other African countries. Household charcoal and fuelwood consumption were income inelastic with significant and positive non-labour income elasticity.

The research effort also evaluated the impacts of potential government policies regarding rural electrification on household biomass energy use. Electricity use had significant but limited effects on fuelwood and total biomass energy consumption. Furthermore, household size, education, and gender composition had the expected effects on household biomass energy and labour use for fuelwood collection. In general, the results support greater policy efforts to resolve the household energy access problem to mitigate the environmental impacts of traditional biomass use and associated societal problems. Concerted policy measures should target promoting rural electrification, education, economic growth, afforestation and sustainable forest management, and promote inter-fuel substitution.

Policy interventions are particularly important for the improvement of rural livelihoods and reduction of environmental degradation. This can be accomplished by efforts to devise, implement, and scale up the use of appropriate practices and technologies to improve agricultural productivity or poverty reduction. Another important approach is the strengthening of afforestation policies to increase access to biomass fuel resources, which will have a key role in helping households cope with fuelwood scarcity. The study findings suggest that creating more off–farm employment, private business opportunities, agricultural intensification through greater investment in improving market access and infrastructure, and improved access to credit and educational opportunities for rural households should all be given appropriate policy attention. The Federal Government of Ethiopia should invest in scaling up existing efforts, helping to increase awareness, and building the capacity to mediate the negative impacts of traditional biomass energy use. Therefore, in designing and implementing rural energy policy, the multidimensionality of fuel-food trade-offs or agricultural linkages need to be taken into account. Hastening the transition towards more environmentally sustainable energy requires a holistic paradigm change that should facilitate investment in renewable energy, create off-farm employment in rural areas, and increase investment in human capital.

This study used a time dependent linear programing model to examine the energy sector of Ethiopia, and evaluated three different demand constraint scenarios. Demand projection was based on initial year empirical data, the projected annual population growth rate, and the GDP growth rate. Biomass energy was uniquely dealt with in the model, which accounted for both solid woody biomass demand and biomass electrical power generation concurrently. Many factors make biomass electrical power attractive, such as its potential to create local economy linkages, create jobs, reduce waste, and rural development advantages. But the sustainability of this approach should be taken into account cautiously. Overall the results suggest that In order to address the deepening rural energy demand-supply gap, Ethiopia could harness its ample and diverse renewable energy resources.

The model exercise helped to evaluate various scenarios regarding Ethiopia’s future energy security. First, the effects of drought or variability in water availability on hydroelectric energy and the country’s energy diversification mix were evaluated. Drought was assumed to have negative effects on hydroelectric energy production over the long term. The results revealed that drought is likely to increase the cost of energy production and alter the overall energy mix of the country. The country will likely need to generate more electricity from relatively expensive renewable technologies to meet projected demand in response to shortfalls in hydroelectric energy from the effects of drought. The second scenario, explored the role of technological and efficiency innovation. In order to cope up with the potential effects of drought on the power sector, Ethiopia should invest in technological and efficiency innovations. The analysis results indicated that technical and efficiency innovations are expected to enhance Ethiopia’s energy security. This would also improve the competitiveness of renewable energy sources that help Ethiopia reduce dependence on drought susceptible hydroelectric energy and reduce associated costs and shadow prices of resources, which is expected to translate into lower prices.

Despite the limitations of the model discussed in Chapter Three, the model provides important insights for improving the sustainability of energy sector development, for not only Ethiopia but also for other developing countries in Sub-Saharan Africa and elsewhere. For Ethiopia and other Sub-Saharan African countries the opportunity to build technical capability from global spill over is high; therefore it should be possible to integrate innovation for improved resource potential development. This will largely depend on how countries are positioned in terms of their regulatory, technical, and institutional capacities.

Renewable energy technologies offer plausible options for decentralized application in off-grid areas in Ethiopia relative to petroleum based power generation or extension of the existing grid. Such efforts may also generate opportunities for local society, the country, or even on a global level. The results of the present benefit analysis of different biogas schemes indicate that subsidized decentralized biogas power generation would generate the greatest benefit and lowest amortization period. Deployment of renewable energy technologies should be facilitated to create greater synergistic linkages with climate change mitigation efforts, sustainable forest conservation initiatives, and sustainable development. An intricate set of factors deter renewable energy diffusion into the remote rural villages of Ethiopia. The major challenge to implementing renewable energy development arises from institutional weaknesses and the lack of effective governance, particularly with respect to biomass energy use and management, as well as the rural energy supply.

5.1. Future research needs

This study explored Ethiopia’s sustainable energy development. Provided Ethiopia strives to harness its renewable energy resources, this study provides empirical based policy insight on how to do so in an economical, resource efficient, and sustainable way. It also provides important guidelines for other sub-Saharan African countries, many of which have similar energy resources and constraints. These analyses focused on the existing biomass energy utilization patterns at household and national levels. Based on the results of this study it is recommended that future research should be based on a more robust panel data approach to identify the effects of fuelwood scarcity on the quantity of household collected and purchased energy resources, and to incorporate market prices and shadow prices.

The energy sector modelling analysis was based on secondary sources and certain assumptions based on reviews from other countries regarding the technical capacity, costs, efficiency, capacity factors, and other model variables. Updated information on solar power generation, which is not yet well developed in Ethiopia, could not be obtained. The cost of renewable technology is dropping significantly and the cost coefficients used in the model for base year 2010 may not reflect the current values. Alternative technological and efficiency innovation growth effects are considered to capture uncertainties, but these deviations should be taken into account cautiously. It would be recommendable to provide a more in-depth analysis of broader energy use systems in agriculture from the water-energy-food nexus perspective. Such approaches should consider energy use beyond subsistence to take into account the roles of energy in contributing to food security and rural development, and related livelihood consequences on poor households. This highlights why attention should be given decentralized energy development, which would requires multidisciplinary experimental research. Opportunities should be opened for experimentation and gathering empirical evidence required for better understanding of the diverse aspects of energy,and food security or agriculture in a more comprehensive, coherent, and coordinated interdisciplinary way. There should also be more research on the ‘rebound effect’ related to technical innovation and efficiency improvement that can arise over time.

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APPENDICES

Table A 3.1. Ethiopia’s existing power plants, 2010

	Plant	Installed capacity (MW)	Mean energy production (GWh/year)	Year operations began	Cumulative hydroelectric installed capacity	Growth rate (%)
1	Koka	43.2	131.12	1960	43.2	
2	Awash II	32.0	161.68	1966	75.2	74%
3	Awash III	32.0	174.81	1971	107.2	43%
4	Finchaa	134.0	912.29	1973 & 2003	241.2	125%
5	Melka Wakena	153.0	559.63	1988	394.2	63%
6	Tis Abbay I	11.4	48.00	1994	405.6	3%
7	Tis Abbay II	73.0	496.69	2001	478.6	18%
8	Gilgel Gibe I	184.0	884.46	2004	662.6	38%
9	Gilgel Gibe II	420.0	1,886.00	2010	1842.6	178%
10	Tekeze	300.0	1,069.00	2010		
11	Beles	460.0	2,050.00	2010		
	ICS Hydro	1,842.6	8,424.00			
12	ICS diesel – aggregate	113.1	582.00	Not available		
13	Aluto Langano geothermal	7.3	13.87	1999		
	Total ICS	1,963.0	9019.60			
	Total SCS	45.7	45.00			
	Total: ICS & SCS	2,008.7	9,064.60			

Sources: MoWE (2010b), EEPCO (2011)

Table A 3.2. Final energy consumption in Ethiopia in tonnes of oil equivalent by energy type, 2005-2009

Year	Petroleum		Electricity		Primary Biomass		Derived biomass		total
	amount	%	amount	%	amount	%	amount	%	consumption
2009	2,152,894	7%	279,736	1%	27,561,198	89%	874,966	3%	30,868,794

2008	2,097,556	7%	268,825	1%	26,810,194	89%	844,556	3%	30,021,131
2007	2,001,349	7%	253,073	1%	26,077,267	89%	815,203	3%	29,146,892
2006	1,718,658	6%	239,932	1%	26,536,257	93%	179,136	1%	28,673,983
2005	1,601,863	6%	206,550	1%	25,815,062	93%	172,682	1%	27,796,157

Source: MoWE (2010a)

Table A 3.3. Final energy consumption in Ethiopia in tonnes of oil equivalent by energy type, 2005-2009

Years	Industry		Transport		Residential		Others	
	amount	%	amount	%	amount	%	amount	%
2009	256,795	1%	1,719,990	6%	28,608,735	93%	283,274	1%
2008	285,449	1%	1,618,997	5%	27,849,431	93%	267,254	1%
2007	289,101	1%	1,518,978	5%	27,055,082	93%	283,731	1%
2006	253,401	1%	1,285,182	4%	26,887,284	94%	248,116	1%
2005	252,860	1%	1,184,029	4%	26,130,969	94%	228,299	1%

Source: MoWE (2010a)

Table A 3.4. Ethiopia's sectoral distribution of power consumption, 2000/01-2011/12 (GWh)

Year	Total electricity consumption	Electricity use in industry	Electricity use in services	Residential electricity use
2011/12	4.39	1.57	1.012	1.58
2010/11	3.84	1.39	0.94	1.47
2009/10	3.98	1.22	0.81	1.19
2008/09	3.13	1.19	0.74	1.18
2007/08	2.94	1.14	0.73	1.03
2006/07	2.79	0.98	0.7	1.06
2005/06	2.4	0.99	0.58	0.79
2004/05	2.7	0.79	0.52	0.72
2003/04	1.84	0.72	0.4	0.59
2002/03	1.7	0.69	0.4	0.59
2001/02	1.62	0.64	0.39	0.58
2000/01	1.41	0.54	0.34	0.52

Source: MoWE (2013)

Table A 3.5. Investment cost and capacity of selected hydroelectric plants in Ethiopia

Plant name	Investment cost (US$ millions)	Capital cost (US$/kW)	Amount (MW)
Fincha Amerti Neshe	276	2,760	100
Fincha	331	2,470	134
Gilgel Gibe I	331	1,839	180
Tekeze	350	1,166	300
Gilgel Gibe II	600	1,500	420
Tana Beles	582	1,337	435
Gilgel Gibe III	1,700	909	1,870
Grand renaissance dam	4,800	914	6,000
Average	1,126	1,636	1,077

Source: Based on unpublished EEPCO reports

Table A 3.6. Ethiopia's prospective hydroelectric projects

Hydroelectric plants to be built by 2015	Planned hydroelectric plants

Name	Installed capacity (MW)	Year of commission	Name	Installed capacity (MW)	Year of commission
Gibe III	1,870	2013	Beko Abo Project	2,100	2023
Fan Project	100	2013	Dabus Project	425	
Genale III	258	2015	Tams Project	1,060	
Halele Werabesa	422	2015	Tekeze Project	450	2020
Chemoga-Yeda	278	2015	Boarder	1,200	2026
Gibe IV Project	1,472	2015	Mendeya 2	2,000	2030
Genale IV	256	2015	Gibe V	662	
Geba I and II	366	2016	Wabi Shebele	460	
Gojeb Project	150	2015	Birbir Project	467	2042
Baro	900		Lower Dedessa	613	
Aleltu	405		Genale Dawa V	100	
Didesa	308	2038	Great Renaissance dam (GERD)	6,000	
Dobus multipurpose	741	2042			

Sources: EEPCO, 2011; EEA; Teshager (2011)

Table A 3.7. Cost and technical data of selected existing hydroelectric plants in Ethiopia

Name of plant	Investment cost (US$ millions)	Capital cost (US$/kW)	Amount (MW)
Fincha Amerti Neshe	276	2,760	100
Fincha	331	2,470	134
Gilgel GibeI	331	1,839	180
Tekeze	350	1,166	300
Gilgel Gibe II	600	1,500	420
Tana Beles	582	1,337	435
Gilgel Gibe III	1,700	909	1,870
Grand renaissance dam	4,800	914	6,000
Mean	1,126	1,636	1,077

Source: Based on unpublished EEPCO reports

Table A 3.8. Cost and technical data for the Ethiopian energy sector model

Power scheme	Capital cost coefficient (US$ millions/MW)	O&M cost coefficient (US$ millions/MW/year)	Initial capacity (MW)	Availability rate (A^i)	Efficiency	Maximum new capacity (MW)
Hydroelectric plants						
Gibe III	1.10	0.04	561	0.90	0.40	1,870
Genale III	1.40		0		0.60	258
Fan Project	2.80		0		0.50	100
Mabil	1.90		0		0.50	1,472
Genale III	1.44		0		0.50	256
Chemoga-YedaI	1.77		0		0.50	278
Halele Werabesa	2.50		0		0.60	422
Gojeb Project	2.60		0		0.70	150
Mendaia	1.00		0		0.70	2,000
GERD	0.90		1,843		0.40	6,000
Tekeze II	1.61		0		0.50	450
Geba I and II	1.62		0		0.70	366

Genale Dawa V	2.80		0		0.80	100
Bako Abo	1.00		0		0.70	2,100
Gibe IV	1.80		0		0.70	1,900
Ganale IV	2.40		0		0.50	420
Kara Dodi	1.80		0		0.60	1,600
Border	1.90		0		0.60	1,200
Dabus Project	2.30		0		0.60	425
Lower Dedessa	2.20		0		0.60	613
Birbir Project	2.30		0		0.50	467
Wabi Shebele	2.40		0		0.60	460
Gibe V	2.10		0		0.40	660
Tams Project	2.00		0		0.70	1,000
Baro	1.02		0		0.60	900
Aleltu	1.57		0		0.60	405
Dedesa	1.70		0		0.60	308
Dobus Multipurpose[24]	2.44		0		0.60	741
Other hydroelectric	1.97		0		0.50	16200
Geothermal plants						
Aluto langano	3.34	0.06	7.3	0.92	0.79	70
Tendaho	3.50		0			100
Abaya	3.80		0			100
Tulu Moye	3.80		0			40
Dofan Fantale	3.80		0			60
Corbetti	4.00		0			1000
Others	3.80		0			3630
		Wind				
Adama	2.29	0.06	0	0.90	0.40	153
Ashegoda	2.41		0			120
Asela	2.50		0			100
Debre Berhan	2.30		0			400
Ayisha	2.30		0			300
Others	2.30		0			8,927
Solar	4.90		0	0.80	0.30	99,999
Thermal	0.80	0.01+0.54 fuel cost[25]	159	0.80	1.00	
Biomass	2.40	0.09		0.99	0.68	

Sources: Based on Heinrich Böll Foundation (2009), EIA (2010), FAO (2010), CRGE (2011), EEPCO (2011), MoWE (2011, 2012, 2013), Guta (2012), and NREL (2012)

Table A 3.9. Cost and technical data for the biomass energy model

Regions	Yield (t/ha/year)	Land cost (US$ millions/ha /year	Forest land in hectares	Maximum land available (grazing + fallow in ha)	Land cost (US$ millions/MW/year	Land cost (US$ millions/t/year
Gambella	0.00001	$8(10^{-6})$	461,586	960	0.0047	$8(10^{-7})$
Oromia	0.0000095	$13(10^{-5})$	2,032,012	1,658,123	0.0080	$1.37(10^{-6})$
Afar	0.000009	$8(10^{-6})$	39,197	893	0.0052	$9(10^{-7})$
SNNPR	0.0000086	$10(10^{-5})$	638,427	424,099	0.0068	$1.2(10^{-6})$

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[24] Because different materials were reviewed regarding the installed capacities of power plants it was not possible to identify the difference between Dobus multipurpose and Dabus project.

Benishangul	0.0000085	$8(10^{-6})$	68,495	9,605	0.0055	$9(10^{-7})$
Amhara	0.000008	$9(10^{-6})$	84,466	462,463	0.0066	$1.1(10^{-6})$
Tigray	0.0000076	$8(10^{-6})$	4,257	40,652	0.0062	$1.1(10^{-6})$
Somalia	0.0000078	$8(10^{-6})$	9,332	32,708	0.0060	$1(10^{-6})$
Harari	0.0000078	$8(10^{-6})$	216	370	0.0060	$1(10^{-6})$

Sources: Based on FAO (2010) and EIA (2010)

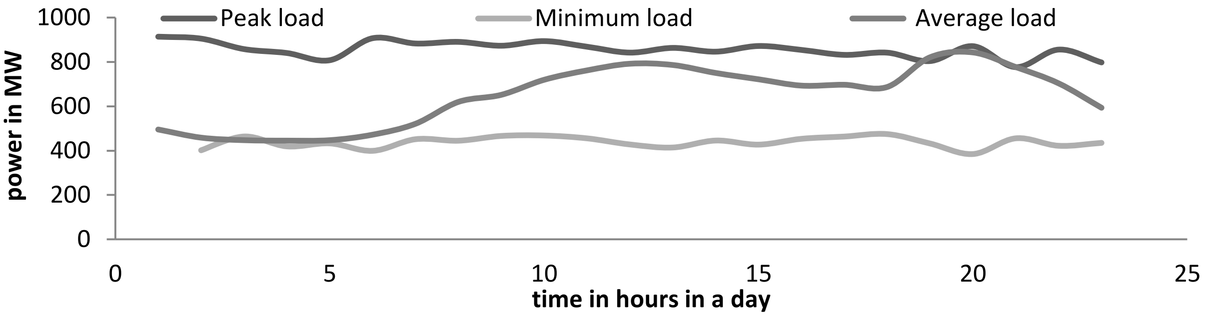

Figure A 3.1. Hydroelectric peak, mean, and minimum loads in Ethiopia, 2010

Source: Based on Tilahun (2011)

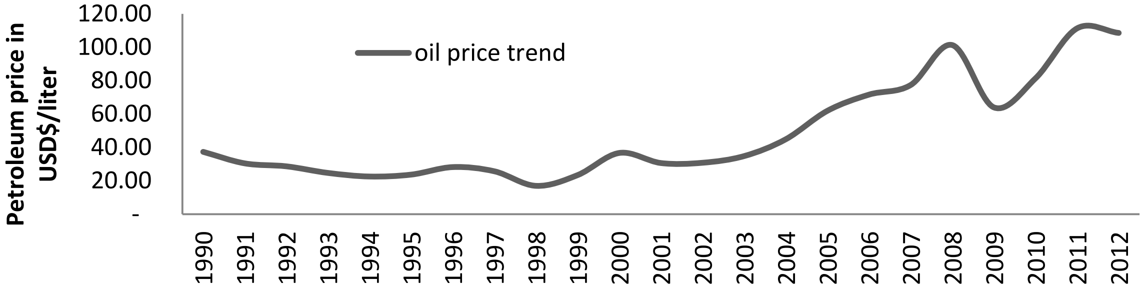

Figure A 3.2. Trends in crude oil spot prices in US$ per barrel, 1990-2011

Source: EIA (2013)

Annex 3.1. Technical annex of model constraints

The model is based on a number of output, demand balance, system reliability, investment capital, land, and resource availability constraints that are explained below.

System reliability constraint: The power supply or installed production capacity of the country must be greater than the expected demand, and should allow for demand peaks above expected levels (reserve requirement). The parameter τ is the peak reserve requirement ratio defined as a percentage of peak demand. X_{td} represents the total demand of peak and off–peak blocks. This constraint was specified as:

$$\sum_{i=1}^{n} A^i(P_i) \geq (1+\tau)X_{td} \tag{1}$$

Electricity demand balance: The demand constraint states that at any moment in time the total sum of power generated from all the energy sources should satisfy the instantaneous power demand. This constraint was specified as:

$$X_{td} < \sum_{i=1}^{n}\sum_{j=1}^{6} P_{ij} \tag{2}$$

Solid biomass energy demand balance: The national solid biomass demand was considered, but supply depends on regionally disaggregated biomass production from forest cover and afforestation/reforestation efforts on marginal land. In any time period the total sum of biomass production from all nine regions of the country must satisfy solid biomass demand. Biomass production in excess of solid biomass demand is used as feedstock for electricity generation based on the constraint described in Eq. (10). The term X_{st} represents the total national biomass energy consumption in period *t*. This constraint was specified as:

$$X_{st} \leq \sum_{m=0}^{9} Q_{sm} \tag{3}$$

Capacity constraint: For each plant the availability rate, A^i, reflects the percentage of time that the plant produces energy. Power plants may be closed due to faults at power stations, transmission or distribution systems, maintenance issues, and in the case of hydroelectric power, due to drought or water shortages in the respective reservoirs, or in the case of solar and wind power due to the intermittent nature of the resource. The available capacity of a power plant was defined as the difference between the actual capacity in excess of the percentage of time it is shut down due to one or more of the aforementioned reasons. For each plant there is a predefined capacity. Thus, each plant's power output cannot exceed its capacity. This constraint was specified as:

$$P_{ijtd} \leq A^i . Q_{ij} \tag{4}$$

Load factor or *plant efficiency*: The plant load factor was defined in terms of the mean ratio of actual power delivered to maximum capacity (peak load). Power load was computed as mean annual power generated from all plants for energy source i divided by its maximum capacity. The ratio is denoted by S. This constraint was represented as:

$$\sum_{i=1}^{6}\sum_{j=1}^{J} Q_{ij} \leq S . X_{td} \tag{5}$$

Resource availability constraint: In any economy there are limited energy resources. Ethiopian maximum renewable energy resource estimate Q^{i}_{MAX} is the maximum potential capacity of resource i, and the sum total of power generated from all plants of source i cannot exceed this maximum available resource. This constraint was expressed as:

$$\sum_{j=1}^{n} Q_{ij} \leq \; Q^{i}_{MAX} \tag{6}$$

Moreover, in each plant there are predefined upper and lower limits on plant capacity. Thus, installed capacity cannot exceed the upper and lower boundaries. The minimum limit is constrained at zero (0) except for the presumed initial capacity on Gilgel Gibe III in 2015. This constraint was specified as:

$$0 \leq Q_{ijt} \leq \; Q^{ij}_{MAX} \tag{7}$$

Capital investment constraint: This constraint indicates that in each period the sum total capital investment or cost of power generation should not exceed the total capital resource of the country. The long-term inflation rate is represented by π. This constraint was specified as:

$$c^{k}_{t} \leq \; K_0\big(1 + (\kappa - \pi)\big)^{t} \tag{8}$$

Land constraint: Biomass feedstock for electrical power imposes additional constraints on land availability. Two types of biomass sources were considered in this model: existing forests and future forested areas. The model assumed that afforestation/reforestation would occur through the conversion of pasture and fallow cropland (F_m). The existing forest cover is represented by (E_m). Thus, in any period the forest area used to supply solid biomass (a_{bmt}) and feedstock for electricity (a_{smt}) should not exceed existing forest area and marginal land available for afforestation/reforestation. This constraint was expressed as:

$$\sum_{t=1}^{T}\sum_{m=1}^{9}\{a_{bmt} + a_{smt}\} \;\leq\; \sum_{m=1}^{9}\{E_m + \quad F_m\} \tag{9}$$

Biomass electricity and solid biomass capacity during each period depend on the total area of forest cover and land allocated to afforestation/reforestation. Therefore, the capacity of a region's biomass energy was specified as:

$$\sum_{m=1}^{9} a_{sm} \leq \; \delta.E_m + \; \rho.F_m, \& \sum_{m=1}^{9} a_{bm} \leq (1-\delta).E_m + (1-\rho).F_m, \tag{10}$$

The levelized cost of each technology was specified as:

$$\mathrm{LCOE} = \frac{\text{life cycle cost}}{\text{life cycle energy}} = \frac{\frac{\mathrm{I_t}}{(1+\mathrm{r})^{\mathrm{t}}} + \sum_{\mathrm{t}=1}^{\mathrm{T}} \frac{\mathrm{A_t}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum_{\mathrm{t}=1}^{\mathrm{T}} \frac{\mathrm{P_{initial}}\,(1-\mathrm{d})^{\mathrm{t}}}{(1+\mathrm{r})^{\mathrm{t}}}} \tag{11}$$

where
I_t = the annual investment cost of the project,
A_t = the annual operation and management costs, and the land rental cost in period *t*,
$P_{initial}$ = the initial energy production in kWh,
d = the rate of devaluation of hardware or equipment,
r = the discount rate,
T = the economic life in years, and
t = the time period in years (= 1, 2, … *t*)