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Dawit Diriba Guta and Jan Börner

Energy security, uncertainty, and energy resource use option in Ethiopia: A sector modelling approach

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Abstract

Ethiopia's energy sector faces critical challenges to meeting steadily increasing demand given limited infrastructure, heavy reliance on hydroelectric power, and underdevelopment of alternative energy resources. The main aim of this paper is to investigate an optimal least cost investment decisions for integrated energy source diversification. We seek to contribute to the relevant literature by paying particular attention to the role of public policy for promoting renewable energy investment and to better understand future energy security implication of various uncertainties. Dynamic linear programming model created using General Algebraic Modelling Systems (GAMS) software was used to explore the national energy security implications of uncertainties associated with technological and efficiency innovations, and climate change or drought scenarios. To cope with the impacts of drought on hydroelectric power production Ethiopia would need to invest in the development of alternative energy resources. This would improve sustainability and reliability, but these changes would also increase production costs. But greater technical and efficiency innovations found to improve electricity diversification, reduce production costs and shadow prices or resources scarcity; and are, thus, key for reducing the risks posed by drought and for enhancing energy security.

Keywords: Energy security, Energy sector model, Climate change, Renewable energy, Technological innovation, Energy efficiency, Ethiopia

JEL classification: Q400, Q410, Q420, Q470

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Abbreviations

CO2	Carbon di Oxide
CRGE	Climate Resilient Green Economy
CSA	Central Statistical Authority
EC	European Commission
EEA	Ethiopian Economics Association
EEPCO	Ethiopian Electric Power Corporation
EIA	Ethiopian Investment Authority
ETB	Ethiopian Birr
FAO	Food and Agriculture Organization of the United Nations
FDRE	Federal Republic of Ethiopia
GAMS	General algebraic modelling system
GDP	Gross Domestic Product
GMI	Global Methane Initiative
GW	Gigawatts
GWh	Gigawatt hours
ICS	Interconnected System
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kW	Kilowatts
kWh	kilowatt hours
LCOE	Levelized Cost of Energy
MoWE	Ministry of Water and Energy
MW	Megawatts
NBE	National Bank of Ethiopia
NEA	National Energy Agency
NREL	National Renewable Energy Laboratory
TWh	Terawatt hours
UNDP	United Nation Development Programme
WHO	World Health Organization

1. Introduction

Energy security is gaining increasing attention worldwide. Energy security encompasses sustainable supply; acceptable sources, costs, and price stability; continued or improved accessibility; and minimising threats to public health or safety and the environment (Kruyt et al. 2009). There are a number of underlying drivers of energy security improvement in developing countries. The vulnerability of national energy sectors to various supply and demand risks is a pressing challenge. 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 (IEA 2013). Ethiopia is among the few remaining countries with a high percentage (over 90%) of its population that continues to be reliant on traditional solid biomass energy use, particularly the use of fuelwood in primitive stoves for cooking purposes (IEA 2013). This overreliance on traditional fuelwood use has contributed to drastic forest cover loss, and the lack of access to more efficient biomass energy technology and fuelwood scarcity have had negative public health and welfare consequences (Guta 2014). The lack of access to modern energy technologies is also a major limitation on sustainable development and poverty alleviation efforts in developing countries. Achievement of many of the 'Sustainable' and 'Millennium Development Goals' will depend on access to affordable, cleaner, and modern energy sources (Cabraal et al. 2005).

The energy sectors of Sub-Saharan African countries have seldom been subject to quantitative model-based investigations. Bazilian et al. (2012) studied electricity sector pathways for Sub-Saharan African until 2030. That study projected future energy demand for the region and predicted "a threefold increase in installed generation capacity occurring by 2030, but more than a tenfold increase would likely be required to provide for full access, even at relatively modest levels of electricity consumption" (Bazilian et al. 2012:1). Other studies have investigated technical and cost aspects of individual and hybrid technologies using the 'levelized cost of energy,' which represents the cost of energy per unit over the life cyle of a power plant or similar facility. A study that computed the levelized cost of photovoltaic (PV) technology in Kenya found that "grid-connected PV systems may already be below that [levelized costs] of the most expensive conventional power plants" (Ondraczek 2014). Other studies have compared the costs of individual technologies across nations, such as Ondraczek et al.'s (2013) evaluation of the solar power markets in Kenya and Tanzania. Other studies have evaluated the cost performance of hybrid technologies at the national level for Senegal (Thiam 2010), Ethiopia (Bekele and Palm 2010), and for Ethiopia, Ghana and Kenya (Deichmann et al. 2011).

Against the backdrop of a rapidly growing economy, vast and available renewable energy resources, and considerable economic and environmental pressures in Ethiopia: quantitative approaches for studying the energy sector, optimal energy resource use, and technological alternatives can help to evaluate future energy security. The Ethiopian Economic Association (EEA) has used both narrow and broad definitions of energy security (EEA 2009). Most narrow definitions focus on maintaining sustainable energy supply to meet demand. Broader definitions include the protection of energy sector infrastructure from criminal or terrorist threats as well as safeguarding against inadvertent failures of normal operations due to the malfunction, damage, and breakdown of related infrastructure, and the resulting effects on national socio-economic and environmental well-being. Energy security is often discussed within the context of the pervasive nature of energy in the sense that it is a vital input for almost every activity and therefore any interruption in its delivery has negative impacts on society (EEA 2009).

Ethiopia faces enormous challenges to electricity generation and transmission. Over the last decade the country has suffered chronic electricity shortages due to rapid economic growth outpacing the development of the energy sector. Electricity generation is heavily reliant on hydroelectric power in the country, which is variable due to a host of factors, including: trade-offs with potable, industrial, and agricultural water needs; frequent and intense droughts; the effects of siltation and sedimentation on dams and reservoirs; and international conflicts over water rights. The World Energy Trilemma (2013) report identified the challenges to 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 hydro [electric] power."

Despite these current circumstances Ethiopia has the potential to become a regional power hub. The geographical location of Ethiopia endows it with exceptional renewable energy resource potential in terms of both diversity and abundance that is yet to be exploited. The

Great East African Rift Valley (GEARV) dissects the country, providing considerable potential for geothermal energy production. The country's proximity to the equator and dry climate provide exceptional potential for solar and wind power development. The country has been described as the 'water tower of Africa' due to the fact that several large rivers drain its extensive highlands. Although most of the overpopulated highlands of the country have long been deforested or denuded of natural vegetation, some fragments of Dry Afro-montane forest, broadleaf rainforest, and native coffee forest remain.

Renewable energy development is a core policy position of the federal government of Ethiopia as a means to both sustain economic growth and meet growing energy demand. The country has targeted renewable energy development as a key driver of its national green economic growth strategy. Various measures have been taken to attract private investment in the energy sector, such as the deregulation of the electricity market.

There is scant quantitative evidence of the various uncertainties involved determining the country's future energy security. In this study we developed a long-term, least-cost energy investment model 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 new renewable energies 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 investment 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? What are the impacts of technological and efficiency innovation on the cost of energy production and the nation's energy mix?

2. Materials and methods

2.1 Model description

The objective of the model was to minimise the expected future cost of energy production over simulation time horizon. The optimization problem was defined in terms of determining plant capacities and energy outputs for the six major energy resources: fossil thermal,[1] 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 (measured in GWh), overall capacity in megawatts (MW), and the quantity (in millions of tonnes) of solid biomass energy for each year.

The model was created using General Algebraic Modelling Systems (GAMS) software.[2] 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.' We modified the original model design to evaluate the effects of different sources of uncertainty, including: changes over time in the rate of technological innovation, efficiency, and of 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 the diversification of the energy sector.

Each model iteration was a long-term simulation of the period 2010–2110 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 beginning at the current gross domestic product (GDP) (2010–2015). Each 5-year period was subdivided into fiscal years with distinct periods reflecting daily and weekly patterns of 'peak' and 'off-peak' electricity demand. 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 system operating and management costs of all plants and energy sources at the time period, $(t)(c_t^o)$, (ii) the total system capital costs of all power plants and energy sources at the time period, $(t)(c_t^k)$, and (iii) the land rental costs for biomass feedstock production at the time period, $(t)(c_t^a)$. The mode equations are described in Box 1.

[1] Diesel thermal refers to power generation from fossil fuels as opposed to geothermal.
[2] From GAMS Software, available at www.gams.com.

Box 1: Equations used in the Ethiopia energy sector model

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

Subject to:

$$\sum_{i=1}^{n} A^i(P_i) \geq (1+\tau)X_{td} \tag{2}$$

$$X_{td} < \sum_{i=1}^{n}\sum_{j=1}^{6} P_{ij} \tag{3}$$

$$X_{st} \leq \sum_{m=0}^{9} Q_{sm} \tag{4}$$

$$P_{ijtd} \leq A^i . Q_{ij} \tag{5}$$

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

$$\sum_{j=1}^{n} Q_{ij} \leq Q_{MAX}^{i} \tag{7}$$

$$0 \leq Q_{ijt} \leq Q_{MAX}^{ij} \tag{8}$$

$$c_t^k \leq K_0\big(1+(\kappa-\pi)\big)^t \tag{9}$$

$$\sum_{t=1}^{T}\sum_{m=1}^{9}\{a_{bmt} + a_{smt}\} \leq \sum_{m=1}^{9}\{E_m + F_m\} \tag{10}$$

$$\sum_{m=1}^{9} a_{sm} \leq \delta.E_m + \rho.F_m; \; \& \sum_{m=1}^{9} a_{bm} \leq (1-\delta).E_m + (1-\rho).F_m \tag{11}$$

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 rate 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 cost per MW of energy by the amount of energy produced (in MW) that 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). We distinguished only two demand blocks for simplicity's sake: 'peak' and 'off-peak' (the sum of 'high,' 'medium,' and 'low' blocks). This is 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). We assumed that this cost would vary over time due to efficiency improvements or 'the learning effect,' which we 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:

$$c_t^o = \sum_{i=1}^{n}\sum_{j=1}^{J}\sum_{t=1}^{T} o_{ijt} \cdot P_{ijt} \cdot \emptyset_{\boldsymbol{d}} \tag{12}$$

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. (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:

$$c_t^k = \sum_{i=1}^{n}\sum_{j=1}^{J}\sum_{t=1}^{T} k_{ijt} \cdot Q_{ijt} \tag{13}$$

The third cost component is land rental opportunity cost, specified as the sum total of the 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 total sum of the two costs depending on which purpose land is allocated to, specified as:

$$c_t^a = \sum_{m=1}^{9} r_{bmt} \cdot Q_{bmt} + \sum_{m=1}^{9} r_{smt} \cdot Q_{smt} \tag{14}$$

The detailed model sets, variables, and parameters are described in Box 2. The model is based on constraints regarding output, energy resource availability, the area occupied by 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 1.

Box 2: Variables and parameters used in the Ethiopia energy sector model

Sets

T set of years from 2010 to 2110
t time in 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$/MW/year).
k_{ijt} the capital costs per MW of capacity (US$/MW)
r_{bm} the land costs per MW of capacity for biomass electricity (US$/MW)
r_{sm} the land costs per tonne of capacity for solid biomass energy (US$/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)

2.2 Data and parameters

The model parameters are presented in Annex 2. The main parameters used in the baseline scenario of the model are presented in Box 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. Biomass electrical energy and traditional solid biomass capacity were estimated based on land use projections using Eq. (11)[3]. Biomass supply was provided by about 3.34 million hectares of existing forest cover (FAO 2010) and 2.63 million hectares of areas of marginal land (fallow crop and grazing land) assumed to be afforested or reforested in all nine regions of the country based on the Ethiopian Agricultural Sample Enumeration conducted in 2010 and 2011 (CSA 2012). Biomass yields per hectare were estimated from annual sustainable yield data (Guta 2012) and forest cover (FAO 2010)[4]. The conversion factor of biomass to electricity was estimated based on a European Commission report (2004) and authors' assumptions[5]. Land rental costs for each region were obtained from the Ethiopian Investment Authority (EIA 2011).

Based on research by EEPCO 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 we used the mean capital cost and plant load

[3] 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.

[4] The mean annual yield at the national scale is about 8.5 tonnes/hectare/year, which varied within a range of 6–10 tonnes/hectare/year across regions.

[5] 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.

factor, which were US$ 1.97 million/MW and 57.5% respectively. Facilities for intermittent energy resources such as solar and wind were assumed to have lower plant factors of 30% and 40% respectively.

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

The amount of financial resources available for energy development is subject to a capital investment cost constraint calculated using Eq. (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 growth rate was 16%. The mean inflation rate for Ethiopia over the period from 1982 to 2010 was 7.5% (World Bank 2013c). Therefore, we set the inflation adjusted annual capital growth rate at 8.5%.

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 week days at 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. We assumed a maximum demand growth rate of 9% and minimum of 6% per year for the 2010–2045 period and assumed that demand will grow at 2.5% 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 (EEPCO 2011).

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 Annex 2. The main limitation on estimating fossil thermal electricity production is 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 Terajoules of petroleum to generate electricity and had an installed fossil thermal power capacity of about 159 MW (MoWE 2011). In the model we used a conversion rate of 0.031 to convert Terajoules to megawatt equivalents. In 2010 the price of petroleum was US$ 0.78/litre 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: 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 for 2,640 hours per year and off-peak load for 6,120 hours per year
τ	0.05 of peak demand in each period to allow for any unexpected power shortfall
A^i	see Annex 2 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, connected systems, 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)

2.3 Description of alternative scenarios

The key assumptions of the baseline and alternative model scenarios are presented in Box 4. Two sets of scenarios were considered. The first set consists of different rates of cost reduction from learning and technological changes 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 innovation and efficiency on the cost of different types of renewable energy are summarised in Annex 3.

Hydroelectric energy has a longevity advantage, but is 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.

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 higher energy production (P_{ij}). Technical innovation also results in a decline in the minimised total cost (Θ) because it is associated with a drop in the 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 fewer 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); affecting the amount of energy produced (P_{ij}) and, through impacts on c_t^o, increasing minimised total cost (Θ). This is because the 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 4).

Box 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

3. Results

3.1 Demand projection

Peak electricity demand is depicted in Figure 1. By 2110 the projected peak demand reaches about 113GW under a high annual electricity demand growth rate and 42.5GW under a low rate. Annual demand for solid biomass energy was projected to reach approximately 88 million tonnes by 2045.

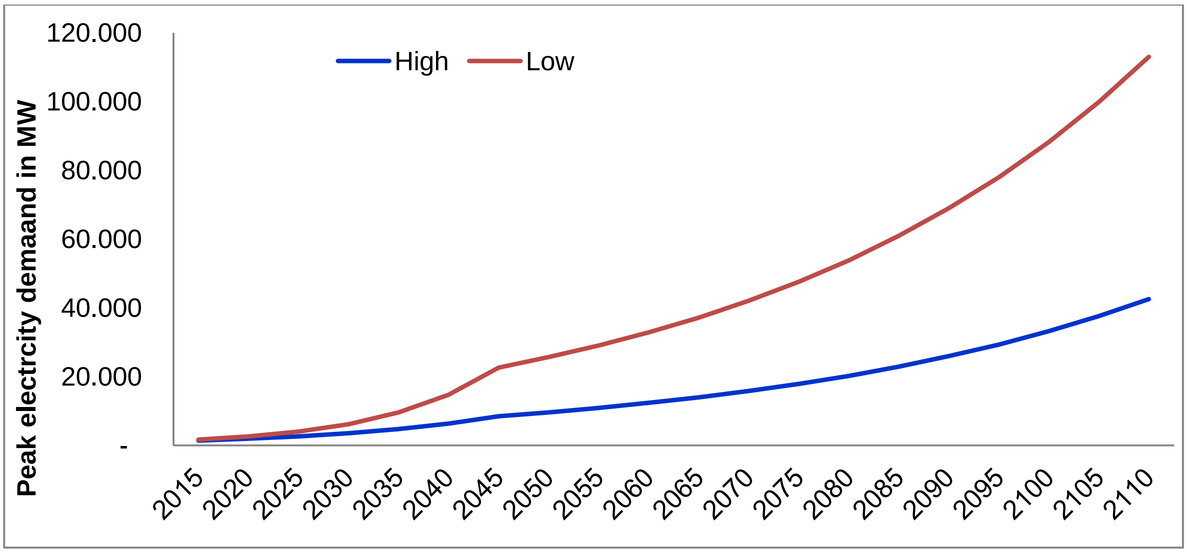

Figure 1: Projected peak electricity demand over time, annual electricity demand growth rate of 9% (high) and annual electricity demand growth rate of 6% (low) over 2010-2045, and 2.5% per year over 2045-2110; Ethiopia energy sector model

3.2 Shadow price of peak electricity demand

Projected shadow prices for peak electricity demand are depicted in Figure 2. 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 Birr 0.572/kWh[6] 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 is predicted to be about US$ 0.027/kWh, which is only

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

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 price (Figure 2). 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.

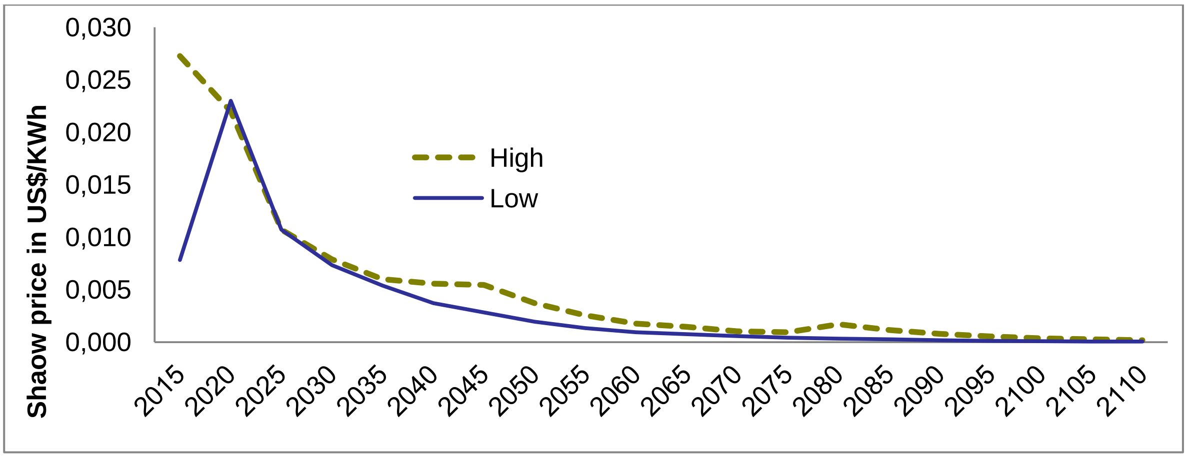

Figure 2: Shadow prices of peak electricity demand over time under high and low electricity demand growth rates, Ethiopia energy sector model

3.3 Electricity production composition in baseline model

Figure 3 and Figure 4 portray electricity production in GWh/year[7] for high and low electricity demand growth rates respectively. Under high electricity demand growth, Ethiopia would generate about 388 Terawatt hours (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 (Figure 3) and because it can satisfy projected demand.

[7] Energy in GWh was calculated from MW by using capacity factor of each of the energy sources as $MWh = MW * cap.factor ** 365 * 24hours; or\ GWh = \frac{(MW*cap.facto*365*24hours)}{1000}$. 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).

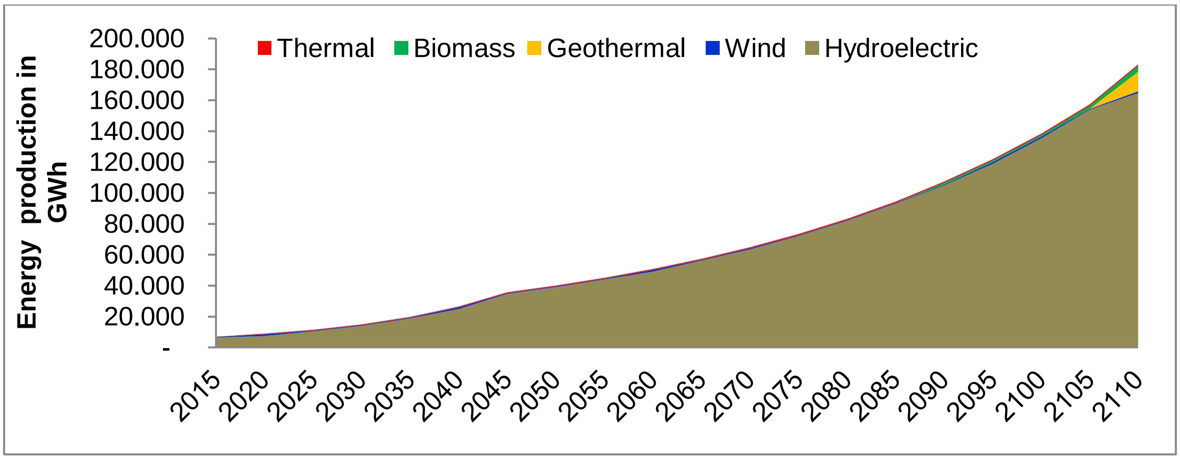

Figure 3: Predicted composition of electricity generation over time under low electricity demand, Ethiopia energy sector model

In the case of high electricity demand growth the country would need to increase electricity production from alternative energy sources (Figure 4). In the latter case geothermal and wind resources were predicted to be fully exploited by 2080 and 2085 respectively, and the country 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 grows to full potential of 4 TWh by 2090 (Figure 4).

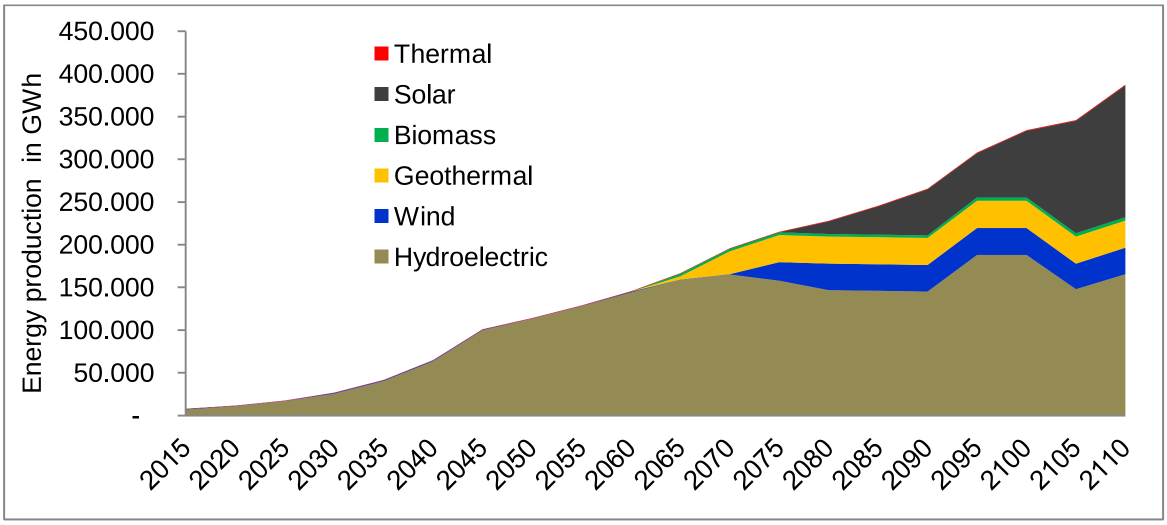

Figure 4: Electricity composition over time under annual electricity demand growth rate of 9%, Ethiopian energy sector model

3.4 Implications of technological and efficiency innovation on energy security

3.4.1 Effects of technological and efficiency innovation on electricity production mix

Greater rates of cost reduction resulting from technological and efficiency innovation were found to promote substitution of new energy resources for established energy sources. Projected electricity production by source is portrayed in figures 5A–5E. 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 5B and 5C). 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 5C). Approximately 11.5 TWh of energy would be produced from wind under the best technological and efficiency innovation scenarios by 2045 (Figure 5B). In contrast, under the baseline scenario additional wind energy production was not projected to occur 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 5D).

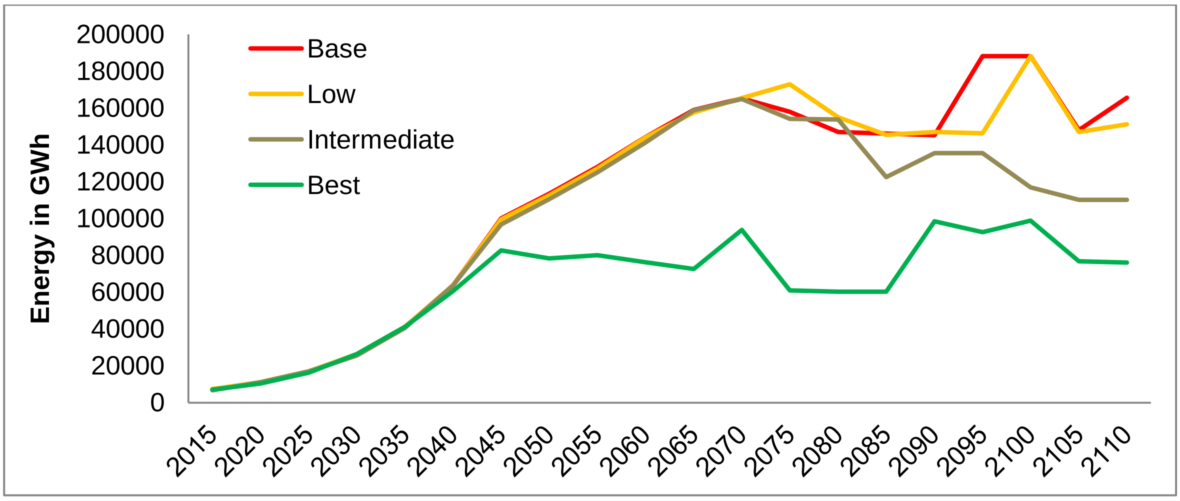

Figure 5A: Hydroelectric production over time under the three technological growth scenarios and the high demand scenario, under annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

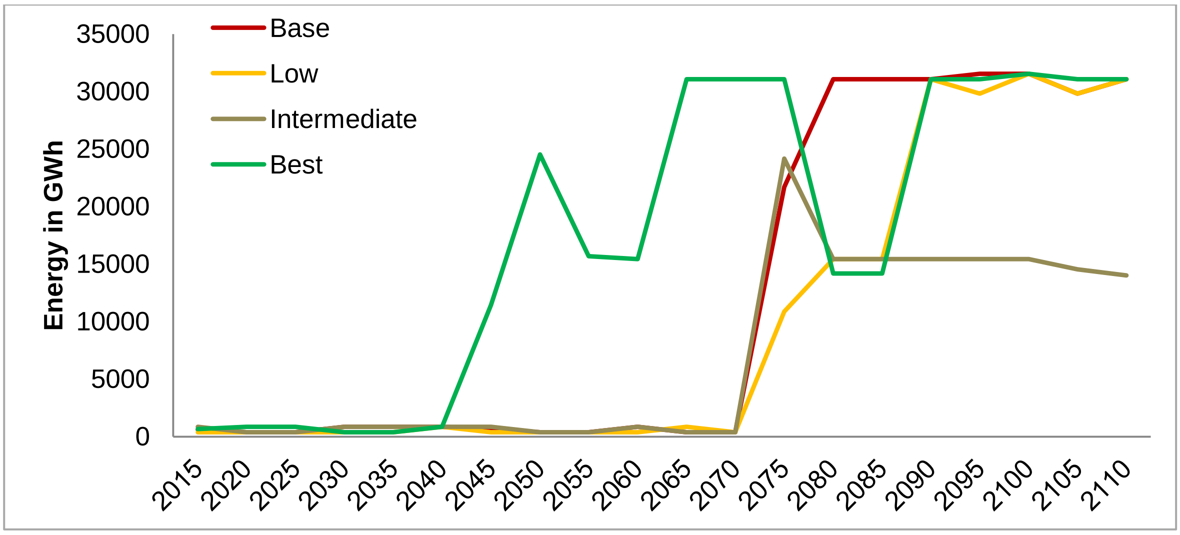

Figure 5B: Wind energy production over time under the three technological and efficiency innovation growth scenarios, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

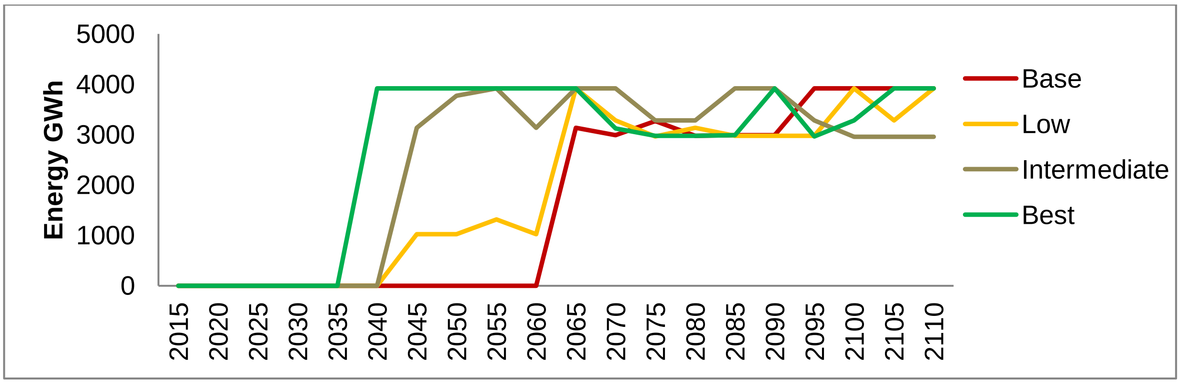

Figure 5C: Biomass electrical energy production over time under the three technological and efficiency innovation growth scenarios, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

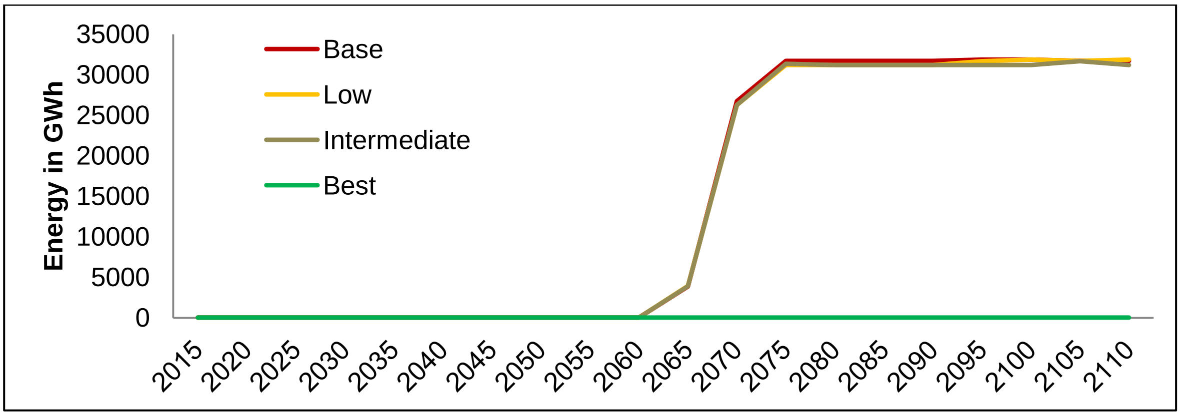

Figure 5D: Geothermal energy production over time under the three technological and efficiency innovation growth scenarios, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

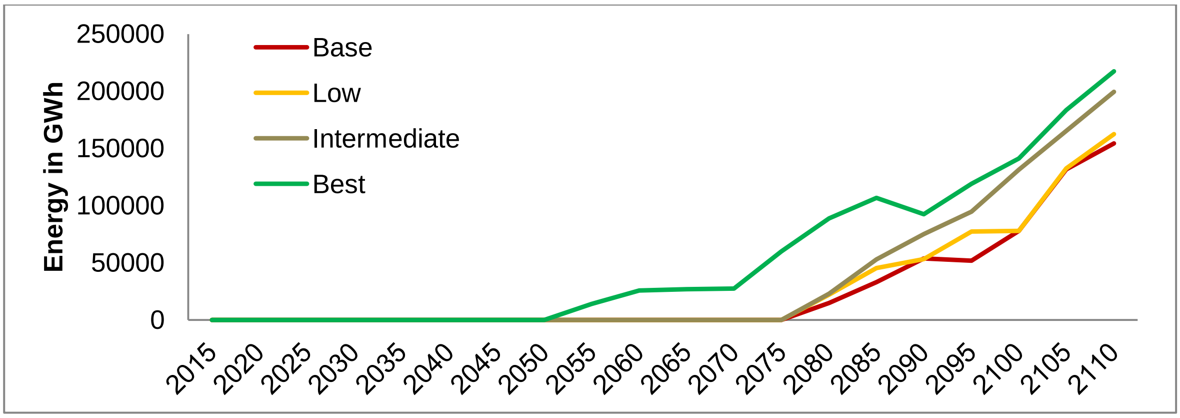

Figure 5E: Solar energy production over time the three technological and efficiency innovation growth scenarios, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

Hydroelectric energy production was projected to fall below baseline scenario levels by about by 20 TWh by 2110 under the best technological and efficiency innovation scenarios (Figure 5A). No additional geothermal energy production would be necessary under the best-case innovation scenario (Figure 5E) due to energy substitution. In general, under the best 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.

3.4.2 Effects of technological and efficiency innovation on the cost of energy production

The effects of different rates of technological and efficiency innovation and land rental on discounted power generation costs are presented in Table 1. 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 1: Predicted declines in the minimised total cost of power generation due to the effects of change in technical 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	–18%

3.4.3 Effects of technological and efficiency innovation on the shadow prices of energy resources

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). The comparison of shadow prices of energy resources is important to inform policy of 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 6. 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 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 decline in general except for a slight increase in the shadow price of biomass electrical energy under the intermediate and best technological and efficiency innovation scenarios. The mean shadow price of energy resources declines 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 is about US$ 0.002/kWh.

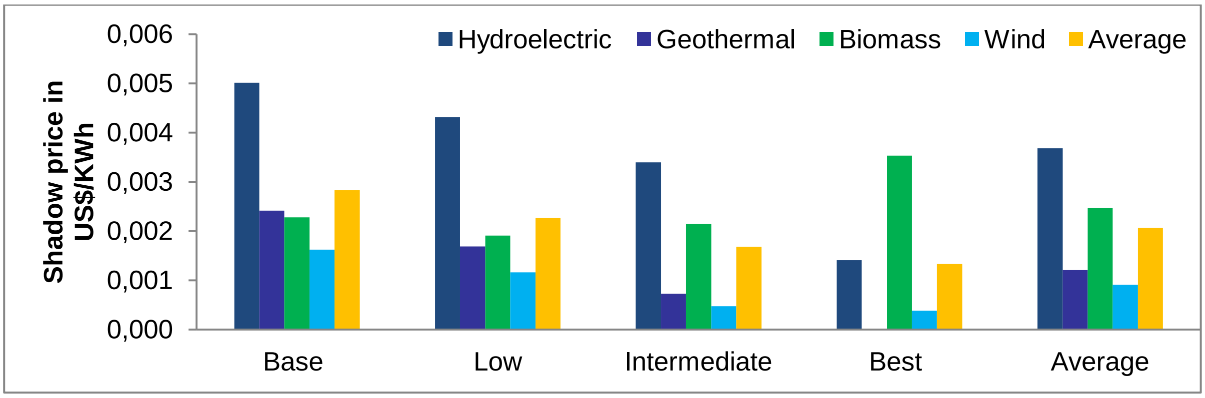

Figure 6: Shadow prices of energy resources under the three technological and efficiency innovation growth scenarios, annual electricity demand growth rate of 9%, Ethiopia energy sector model

3.5 Climate change or drought and energy security implications

3.5.1 Effects of drought on electricity production mix

There are risks associated with Ethiopia's heavy reliance on hydroelectric energy. There is considerable uncertainty about how climate change may affect energy production in the country; however, some studies indicate that hydroelectric power generation is vulnerable to drought or water scarcity. Estimated minimum, mean, median and maximum energy production levels are depicted in figures 7A–7E. 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 adverse effects are more likely to manifest over the long term (Figure 7A).

To cope with the effects of climate change on the energy sector the country should diversify energy production with alternative sources. Our 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 7B [geothermal], Figure 7C [wind], Figure 7E [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 7D).

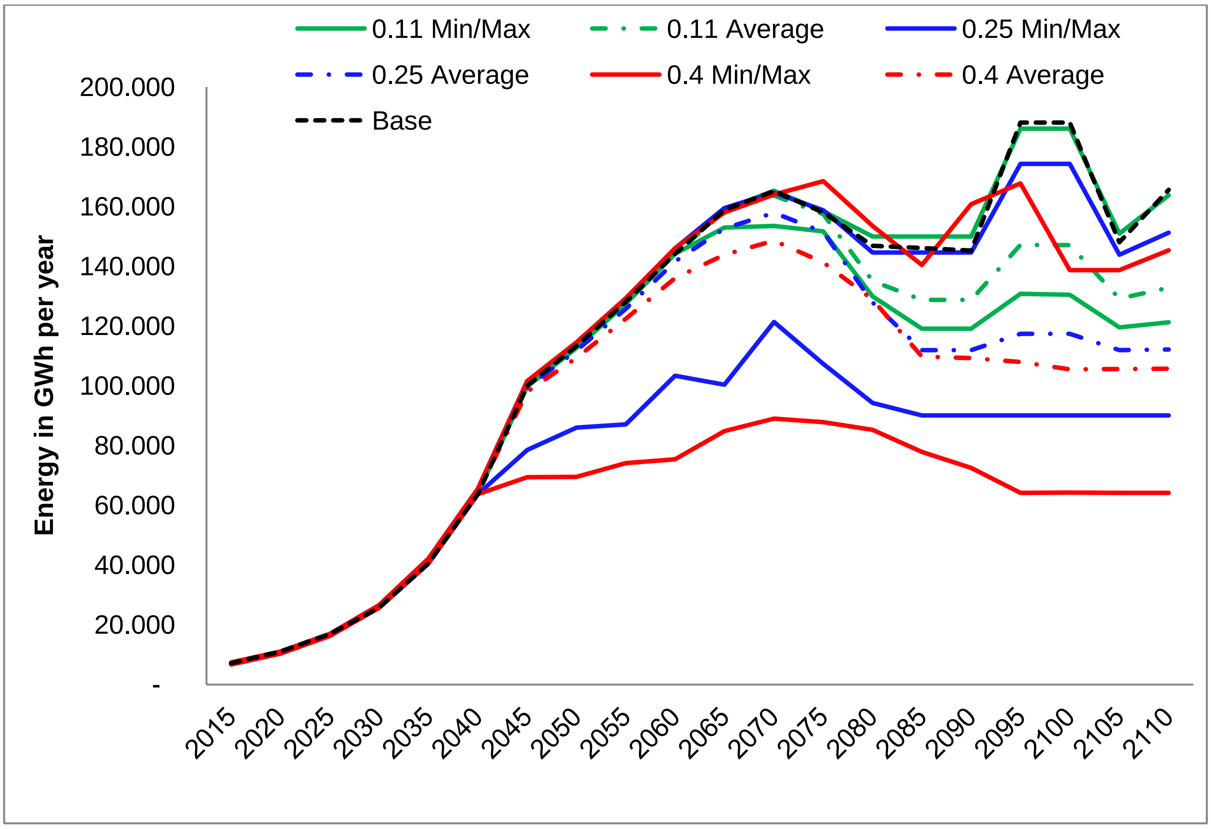

Figure 7A: Effects of water availability variability (using standard deviations of 0.11, 0.25 and 0.40) on hydroelectric energy production over time, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

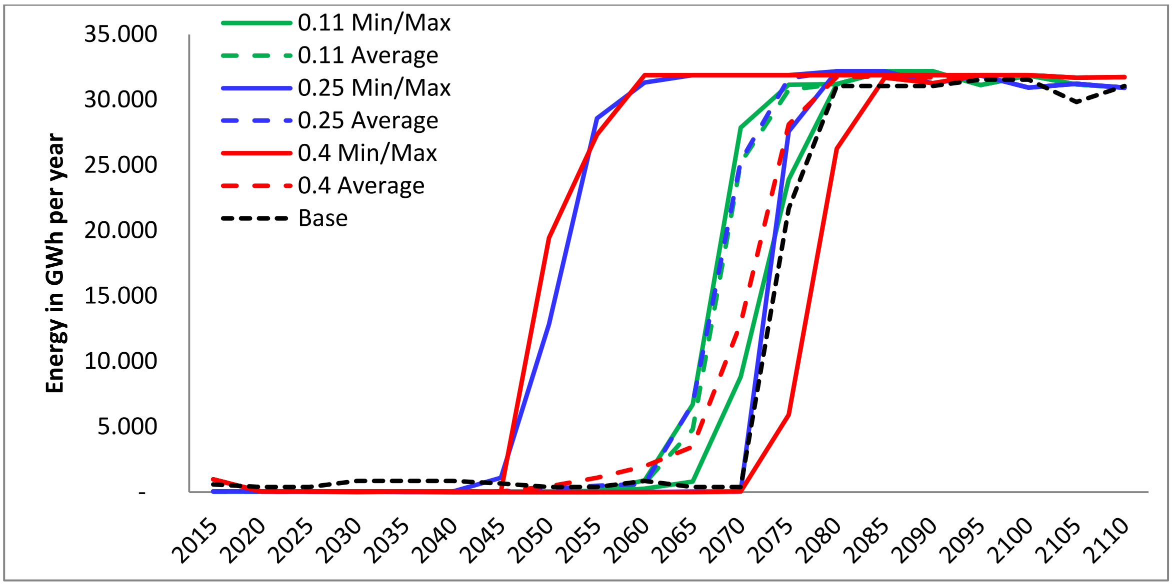

Figure 7B: Effects of water availability variability (using standard deviations of 0.11, 0.25 and 0.4) on wind energy production over time, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

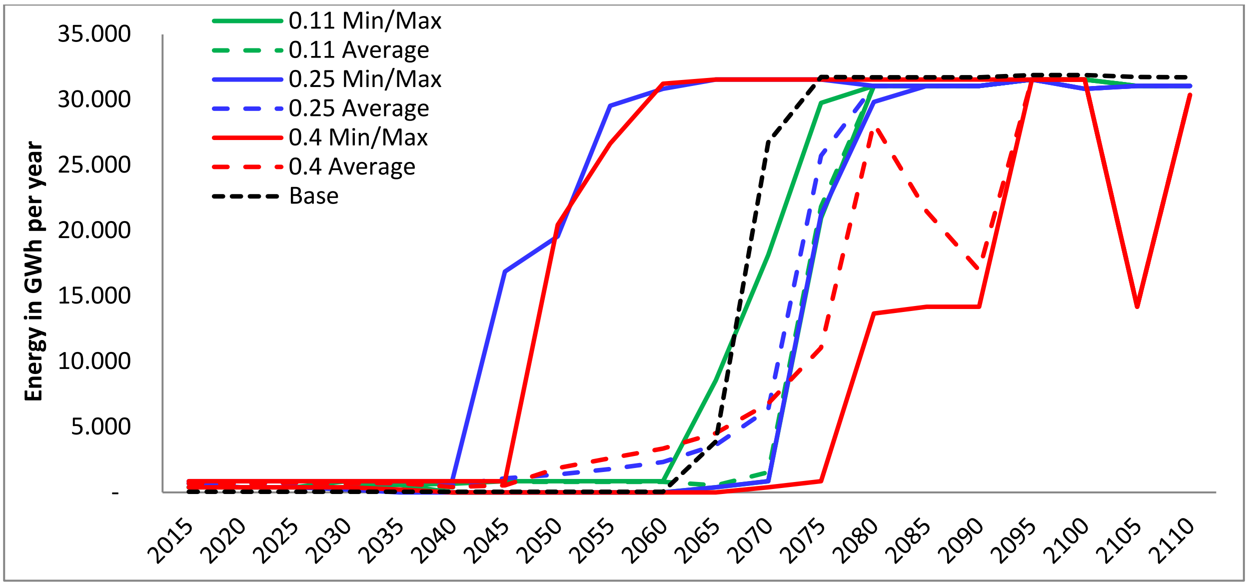

Figure 7C: Effects of water availability variability (using standard deviations of 0.11, 0.25 and 0.4) on geothermal energy production over time, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

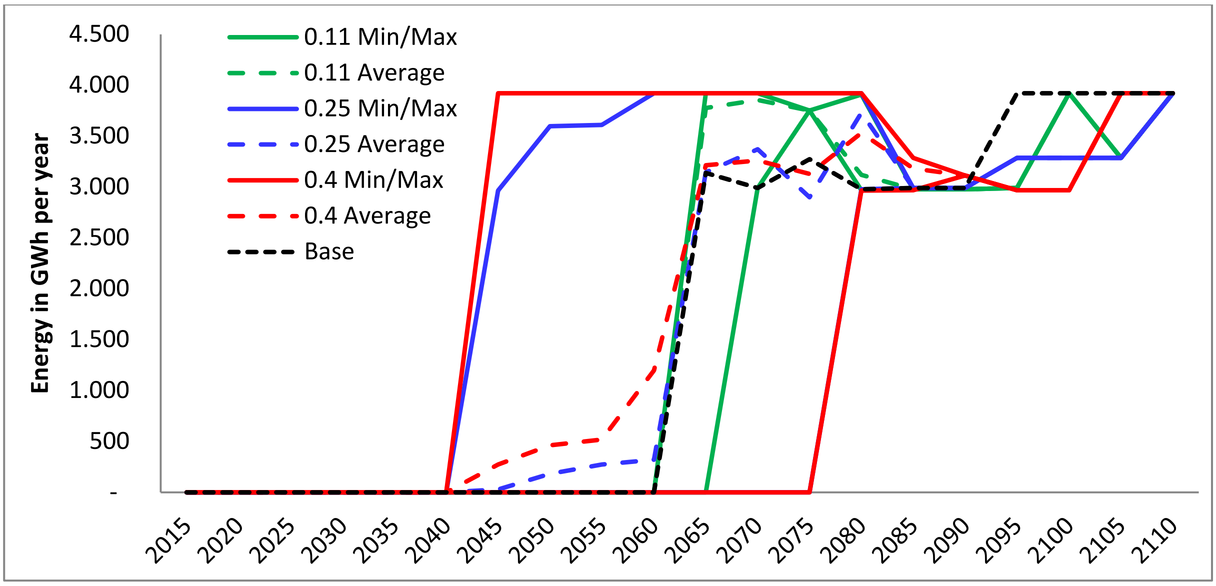

Figure 7D: Effects of water availability variability (using standard deviations of 0.11, 0.25 and 0.4) on biomass electrical energy production over time, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

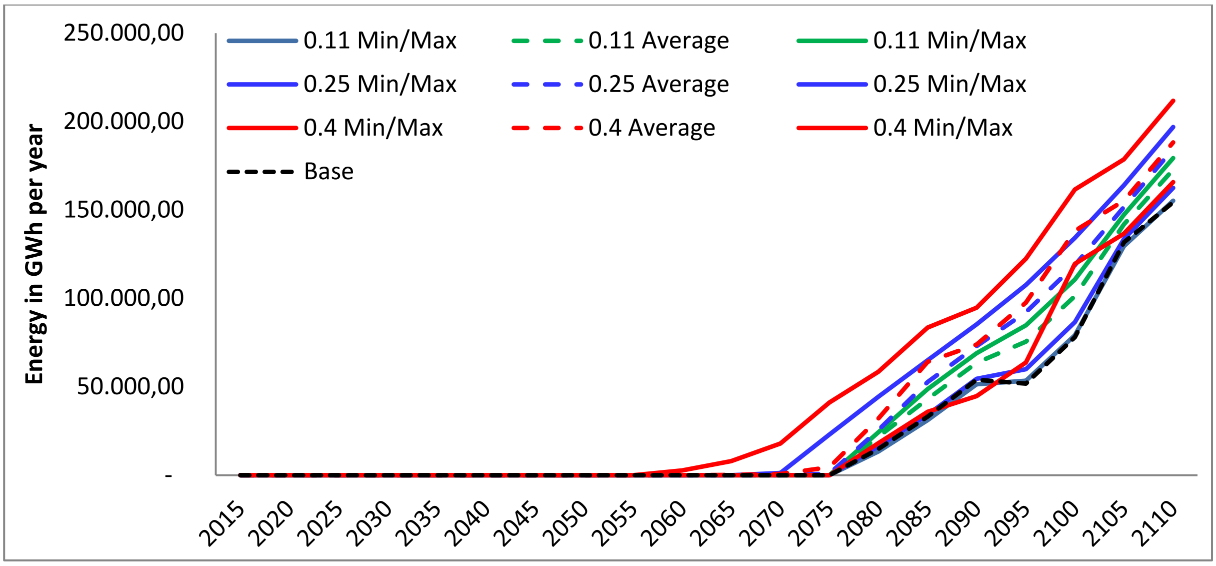

Figure 7E: Effects of water availability variability (using standard deviations of 0.11, 0.25 and 0.4) on solar energy production over time, annual electricity demand growth rate of 9%, Ethiopia energy sector model (GWh/year)

3.5.2 Effects of drought on energy production costs

The effects of drought on discounted minimised energy production cost relative to the baseline model are presented in Table 2. Costs are 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 2).

Table 2: Predicted effects of drought on the minimised cost of energy production for different standard deviation levels of water availability variability, 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

3.6 Energy source competitiveness: Levelized cost of energy (LCOE)

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 the initial investment costs, annual operating costs, interest rates, and devaluation rates of power generation as described in Eq. (11) in Annex 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 is the highest in this context (about US$ 0.189/kWh). Biomass electrical energy and wind are the most expensive sources after solar with LCOE values of US$ 0.122/kWh and US$ 0.102/kWh respectively. Hydroelectric and geothermal have lower LCOE values of about US$ 0.051/kWh and US$ 0.080/kWh respectively (Table 3).

3.7 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 these resources in Ethiopia. To improve energy access in remote communities where renewable resources are abundant but financial resources are minimal the optimal policy strategy for Ethiopia would be to provide incentives for private, household or cooperative associations to harness renewable resources. Related policies such as capital subsidies should 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 invest or 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 comparisons among technologies based on the annualized present capital cost per unit. Capital subsidies were estimated based on 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. The base year capital cost assumptions and plant longevity of each energy type are given in Annex 2. The Ethiopian government should provide capital subsidies of about US$ 263 million/kW for solar energy to make it competitive with hydroelectric energy, followed by geothermal (US$ 118/kW), biomass (US$ 120/kW), and wind (US$ 115/kW).

Table 3: Estimated capital subsidies required to make alternative renewable technologies competitive with hydroelectricity (in US$ millions/kW) and the levelized cost of energy (in US$/kWh), Ethiopia energy sector model

	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

4 Discussion of the limitations of the model and policy implications

The model does offer many important empirical insights. We explicitly incorporated land and capital resource constraints. Land constraints considered were only for biomass energy. Despite the lack of data, land constraints with respect to other renewable (wind and solar) have increasingly become a concern, which future research needs to investigate. Second, we incorporated forest derived biomass energy for traditional use and electricity generation into the model. Third, we investigated uncertainties related to climate change induced drought and technological and efficiency innovation, and drew energy security implications. Finally, we estimated the scarcity value or shadow price of renewable energy resources and evaluated effect of technological and efficiency innovation on shadow prices or resource scarcity.

Our 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 we created relies on perfect foresight regarding future energy demand growth and presumed to depend on economic and population growth rates. Despite our 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 be captured in the model.

There are many caveats regarding the results of this model that future research efforts should take into account. Higher capacity and energy production from alternative technologies appear to increase only over the long term. This is because we allowed substitution 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 programming models on energy systems, we did not impose a positive lower boundary 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, we could not update the cost parameters because the model parameters were all based on base year values. Cost coefficients for newer renewable technologies, especially solar, are not available for Ethiopia. We reviewed relevant literature 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. We evaluated alternative scenarios of technological and efficiency innovation, but these changes were not sufficient to make alternative technologies competitive with hydroelectric power in the short to midterm. Our 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 our 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 effects of climate change are debatable. In the Ethiopian highlands precipitation may increase rather than decrease, which may actually increase water availability for hydroelectric power generation. However, if increases in precipitation only occur during the rainy season this may not translate to increased hydroelectric energy production as water scarcity normally arises during the dry season. Hence, 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 directly affect the capacity of hydroelectric reservoirs. Ethiopia is currently building large hydroelectric project. The classic investment maxim about ‘putting all of your eggs in one basket’ increasing risk or 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. Nonetheless, 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.

The primary adaptation measure to drought in Ethiopia so far is increased use of fossil thermal, to cope with power rationing or blackouts. 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 (i.e. 2007–2009). One limitation of the model is that the lack of detailed data on non-renewable energy resource potential of the country prevented us from incorporating relevant parameters. Ethiopia relies entirely on petroleum imports, as domestic sources have not yet been explored or exploited. Ethiopia may be able to explore and exploit its fossil resources more cheaply than the current costs of importing them. In this modelling exercise we assumed that fossil thermal electricity production depends on fixed annual growth rates. Due to the lack of detailed data on thermal plants, we did not identify the different fuels (gas, coal, and diesel). Despite technological and efficiency improvements among alternative energy resources, electricity generation from non-renewable resources remains the cheapest option for Ethiopia over the short or midterm. Nevertheless, the CO_2 emissions of electricity generation, which we did not consider 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. Besides, over the long term the Ethiopian federal government plans to develop nuclear energy capacity, which would significantly affect potential energy diversification pathways.

In this modelling exercise we also applied a range of standard deviation values (0.11–0.40) to capture uncertainty as discussed above. We attempted to measure 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 cost of energy production could be expected, which is relatively straightforward. The country needs 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. Due to the fact that climate change is a dynamic process and its actual impacts on electricity generation are not yet empirically determined given limited information.

Two policy options were investigated in this study: capital subsidies to make alternative technologies competitive with hydroelectric power and technological and efficiency innovation. 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 technologies, 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 innovation, 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 to reduce the risks of climate change would be to invest in technological and efficiency innovations or adaptability and capacity building or training. Alternative renewable energy sources can offer long-term environmental, economic, and public health benefits. Our 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 technological innovation and efficiency, reflecting reduced resource scarcity and conforming to the hypothesis that technological and efficiency advancements are the engine of 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 the degree to which they result in cost reductions and whether they increase energy consumption, which in turn may partially offset any positive gains. Appropriate empirical research attention should be given to these issues in the future.

5. Conclusion and policy recommendations

Ethiopia needs to invest in relatively expensive renewable energy resources in pursuit of green energy development, poverty alleviation, and energy security; however, such an effort is hindered due to the high capital costs of 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 R&D or the development of local skills and technical capacity. In the world of constrained resource availability technological and efficiency innovations can be an engine of growth. Increases in cost reductions from technological and efficiency innovations were associated with decreases in the shadow prices of energy production. This reflects the economic benefits of technological and efficiency innovations due to their role in reducing resource scarcity. Such 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. 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 should offer incentives for technological and efficiency innovation, R&D, and human skill development with respect to renewable energy using policies tools such as capital subsidies that enhance the competitiveness of alternative energy sources.

References

Baker, E., Fowlie, M., Lemoine, D., and Reynolds, S.S., 2013. The Economics of Solar Electricity. Annual Review of Resource Economics, 5: Submitted. Doi: 10.1146/ annurev-resource-091912-151843

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R., and Yumkella, K., 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy, 39, 7896–7906.

Bekele, G., and Palm, B., 2010. Feasibility study for a standalone solar–wind-based hybrid energy system for application in Ethiopia. Applied Energy, 87:487–495.

Branker, K., Pathak, M., and Pearce, M., 2011. A review of solar photovoltaic levelized cost of electricity. Renewable and Sustainable Energy Reviews, 15: 4470–4482.

Cabraal, R.A., Barnes, D.F., and Agarwal, S.G., 2005. Productive uses of energy for rural development. Annual Review of Environmental Resources, 30: 117–144.

Central Statistical Authority (CSA), 2012. Agricultural sample survey 2010/2011. Addis Ababa, Ethiopia.

Chang, Y., and Hin Tay, T., 2006. Efficiency and deregulation of the electricity market in Singapore. Energy policy, 34, 2498–2508.

Climate Resilient Green Economy (CRGE), 2011. Ethiopia's Climate Resilient Green Economy: Green Economy Strategy. Addis Ababa: FDRE.

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

Ethiopian Economics Association (EEA), 2009. Report on the Ethiopian Economy. Energy Resources, Demand, Supply and Access in Ethiopia, 211–334. Addis Ababa, Ethiopia.

Ethiopian Electric Power Corporation (EEPCO), 2011. Data base of the Ethiopian electric power corporation on sales consumption by tariff category from 1973–2003 EFY. Addis Ababa, Ethiopia.

Ethiopian Investment Authority (EIA), 2010. Factor cost. (available at: http://www.ethiopiaembassy.ru/pages/docs/ETHIOPIAN_INVESTMENT_AGENCY_FACTOR_COSTS.pdf, accessed on 28/03/2013).

European Commission (EC), 2004. Bioelectricity: Efficient and clean production of electricity from biomass via pyrolysis oil and hydrogen utilizing fuel cells. 1 EC RTD RENEWABLE

ENERGIES PRESS BRIEFING Uppsala, 16 November. (available at http://ec.europa.eu/research/energy/pdf/04 _bioelectricity_en.pdf, accessed on 21/02/2013).

Food and Agriculture Organization of the United Nations (FAO), 2010. Global forest resource assessment, country report Ethiopia. Forest Resources Assessment, FRA2010/065. Rome.

Funk, J., and Marshall, M., 2012. Mapping recent decadal climate variations in precipitation and temperature across Eastern Africa and the Sahel, pp 331–358 in Remote sensing of drought—Innovative monitoring approaches, Wardlow, B., Anderson, M., and Verdin, J., (eds.), New York, CRC Press.

Global Methane Initiative (GMI), 2011. Ethiopia Solid Waste & Landfill [Country Profile and Action Plan] Community Development Research (available at: https://www.globalmethane.org/documents/landfills_cap_ethiopia.pdf, accessed on 20/06/2013).

Guta, D., 2012. Assessment of Biomass Fuel Resource Potential and Utilization in Ethiopia: Sourcing Strategies for Renewable Energies. International Journal of Renewable Energy Research, 2: 132–139.

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

Heinrich Boell Foundation, 2009. A Preliminary assessment of risk and opportunities for the power sector, 2009. Forum for the Environment, Diversity and Security of the Ethiopian Power System, 2009. Heinrich Boell Foundation. Addis Ababa, Ethiopia.

International Energy Agency (IEA), 2009. Energy Balance for Ethiopi (available at: http://www.iea.org/STATS/balancetable.asp?COUNTRY_CODE=ET, accessed on 10/05/2013).

International Energy Agency (IEA), 2010. Wind: 2009 Annual Report, IEA Wind Energy Systems. Paris, France.

International Renewable Energy Agency (IRENA), 2012a. Renewable energy technologies: Cost analysis series; Volume 1: Power Sector Issue 2/6, Concentrating Solar Power.

International Renewable Energy Agency (IRENA), 2012b. Renewable energy technologies: Cost analysis series; Volume 1: Power Sector Issue 5/6, Wind

International Renewable Energy Agency (IRENA), 2012c. Renewable energy technologies: Cost analysis series. Volume 1: Power Sector Issue 1/5, Biomass for Power Generation.

Kruyt, B., vanVuuren, D., deVries, H., and Groenenberg, H., 2009. Indicators for energy security. Energy Policy, 37: 2166–2181.

Ministry of Water and Energy (MoWE), 2011. Joint energy report for Africa, collected data by fuel type, Database, Addis Ababa, Ethiopia.

Ministry of Water and Energy (MoWE), 2012. Scaling-Up Renewable Energy Programme Ethiopia Investment Plan. January, Addis Ababa, Ethiopia.

Ministry of Water and Energy (MoWE), 2013. Ethiopia's Renewable Energy Power Potential and Development Opportunities. Presented at IRENA, Abu Dhabi, United Arab Emirates.

National Bank of Ethiopia (NBE) 2011. 2010/11 Annual report. (available at: http://www.nbe.gov.et/pdf/annualbulletin/Annual%20Report%202010-2011/Annual%20Report%202010-2011.pdf, accessed on 12/06/2013).

National Energy Agency (NEA)/International Energy Agency (IEA), 2010. Projected cost of generating electricity–2010 edition. Paris.

National Renewable Energy Laboratory (NREL), 2012. Cost and performance data for power generation technologies. (available at: http://bv.com/docs/reports-studies/nrel-cost-report.pdf, accessed on 05/04/2013).

Ondraczek, J., 2014. Are we there yet? Improving solar PV economics and power planning in developing countries: The case of Kenya. Renewable and Sustainable Energy Reviews 30: 604–615.

Ondraczek, J., Komendantova, N., and Patt, A., 2013. WACC the dog: The effect of financing costs on the levelized cost of solar PV power. Working Paper FNU-201. University of Hamburg, Research Unit-Sustainability and Global Change.

Thiam, R., 2010. Renewable decentralized in developing countries: appraisal from microgrids project in Senegal, in: Renewable Energy, 35 (8): 1615–1623.

United Nation Development Programme (UNDP), 2013. Human Development Report 2013 Media Toolkit (available at: http://hdr.undp.org/en/content/ human-development-report-2013-media-toolkit, accessed on 20/09/2013).

Winkler, H., Hughes, A., and Haw, M., 2009. Technology learning for renewable energy: Implications for South Africa's long-term mitigation scenarios. Energy Policy, 37: 4987–4996.

Woody Biomass Inventory and Strategic Planning Project (WBISPP), 2004. Forest Resources of Ethiopia. Addis Ababa, Ethiopia.

World Energy trilemma2013 (available at: http://www.worldenergy.org/data/sustainability-index/country/ethiopia/2013/ (accessed on 31/07/2014).

World Health Organization (WHO), 2009. Country profile of Environmental Burden of Disease. Public Health and the Environment Geneva. (available at: http://www.who.int/quantifying_ehimpacts/national/countryprofile/ethiopia.pdf?ua=1, accessed on 23/06/2014).

World Bank, 2013a. Electric power consumption (kWh per capita) (available at: http://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC, accessed on 30/01/2013).

World Bank, 2013b. Data catalogue Ethiopia (available at: http://data.worldbank.org/summary-terms-of-use, accessed on 07/07/2013).

Annex 1: Technical annex, 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 the 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. Hence, 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:

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

Hence, biomass electricity and solid biomass capacity during each period depend on the total area of forest cover and prospective 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*)

Annex 2: Cost and technical information for the Ethiopia energy sector model

	Capital cost coefficients (US$ millions/MW)	O&M cost coefficients (US$ millions/MW/year)	Plant longevity	Initial capacity	Availability	Plant efficiency
Hydroelectric	1.87	0.04	50	561	0.90	0.58
Geothermal	3.72	0.06	30		0.92	0.79
Wind	2.35	0.06	25		0.90	0.40
Solar	4.9	0.06	25		0.80	0.30
Fossil Thermal	0.83	0.01	25		0.80	0.30
Biomass	2.4	0.09	25		0.99	0.68

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

Annex 3: Estimated declines in the cost of renewable energy technologies 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)