Power to the People: Increasing Electricity Access, Connectivity, and Usage in Uganda

Energi til folket: Tilgang til og bruk av strøm i Uganda

Philosophiae Doctor (PhD) Thesis

Grace Alinaitwe

Norwegian University of Life Sciences
School of Economics and Business (HH)

Ås (2024)

Thesis: 2024:44
ISSN: 1894-6402
ISBN: 978-82-575-1916-

Dedication

I dedicate this work to my parents: Lawrence Bategeka and Angela Bategeka, you sacrificed a lot to give me a foundation. You loved me unconditionally. Thank you for always believing in me and encouraging me to aim higher.

Acknowledgement

I am honored to thank everyone who made this PhD plausible.

First and foremost, I would like to thank the almighty God because it was His will that I get this PhD. It is by His grace that I made it this far amidst many challenges. No wonder the African saying "Ekiterekerwa omunaku tekivunda"! Meaning, "what was meant to be, will be".

To my Supervisors, Prof. Ragnar Øygard, Prof. Olvar Bergland, and Prof. Stein Holden, thank you for being determined to see me run to the finish line. Thank you Prof. Olvar Bergland for not giving up on me. You single-handedly picked me up when I was crushed down, and all hope was gone. Prof. Arild Angelsen, thank for the time, help, and friendship. Prof. Ståle Navrud and Prof. Ole Gjølberg, thank you for the useful comments. Prof. Kyrre Rickertsen, thank you for the teaching assistant opportunity you gave me, for the different course units.

I would like to thank the NORHED Program of the Norwegian Agency for Development Cooperation (NORAD) and Makerere University Business School (MUBS) for the funding.

To my family members, thank you for looking after my children when I left them behind to start this journey. Mum (Angela Bategeka), thank you for the endless prayers, advice and support, both mental and spiritual. Dad (Lawrence Bategeka (Dr)) thank you for all the advice and best wishes. Florence Barugahara (Dr), what more can a person wish for when they have a loving, and caring sister like you? Thank you for sparing your time to read, correct and even advise me throughout this research work. Mildred Barungi (Dr), you have taught me what it takes to be a big sister. First, you insisted that I must climb the ladder to your level (PhD), secondly, you made it easier for me to climb. Any time I needed data, you personally called UBOS members, and ensured that I got the data. Gorreth Ayebale, thank you for being a loving sister who became a mum to my boys at the time I left for Norway. To my other siblings Donald Bakire, Moses Bigabwa (Obeng & Evers), Solomon Baguma, Flavia Nasobora, Roselyne Kyalisiima, and Justine Mpairwe, thank you for the prayers. Surely given a chance, I would still choose the same team of siblings. To my children, Amaani, Agonza and Ayeeta, thank you for being such a pillar of support. You prayed for my success and believed in me. You ran the home in my absence. I love you, my sons.

Table of Contents

Abbreviations and Definitions

AIC Akaike Information Criterion

ARDL Auto Regressive Distributed Lag

BIC Schwartz's Bayesian information criteria

CPI Consumer price index

ERA Electricity Regulatory Authority

KPSS Kwiatkowski‑Phillips‑Schmidt‑Shin

OLS Ordinary Least Squares

PPA Power Purchasing Agreement

REP Uganda's Rural Electrification Project

SDGs Sustainable Development Goals

TSO Transmission System Operation

UBOS Uganda Bureau of Statistics

UEB Uganda Electricity Board

UEDCL Uganda Electricity Distribution Company Limited

UEGCL Uganda Electricity Generation Company Limited

UETL Uganda Electricity Transmission Company Limited

VAR Vector autoregression

VECM Vector Error Correction Model

List of Papers

Paper 1: Household Energy Demand in Uganda: Estimation and Policy Relevance.

(An older version published in "Energy, COVID, and Climate Change", 1st IAEE Online Conference, June 7-9, 2021, International Association for Energy Economics.)

Paper 2: Powering Ugandan households: What determines Solar Photovoltaics adoption?

(An older version published in *Journal of Service Science and Management*, 16(4), 2023, DOI: 10.4236/jssm.2023.164022)

Paper 3: Assessing the relationship between fuel and charcoal prices in Uganda.

(Grace Alinaitwe and Olvar Bergland; forthcoming in *Economies*)

Paper 4: Economic Growth–Electricity Consumption Linkage in Uganda Revisited.

(Grace Alinaitwe and Olvar Bergland; a slightly different version published in *Journal of US-China Public Administration*, 20(2), 2023: 111-126.)

Abstract

The thesis is a collection of four empirical papers on energy-related issues in Uganda. They cover issues related to electricity demand, adoption of photovoltaic energy (PV), charcoal prices, and linkages between electricity consumption and economic growth.

The first paper examines household energy demand in Uganda. Increasing electricity use at the household level provides an opportunity to improve welfare and avoid environmental and public health externalities from the dominant energy sources: firewood and charcoal. The Uganda 2018/2019 Living Standards Measurement Study (LSMS) household data are used to study price elasticities of different energy types. Price and income elasticities are derived through applying a two-stage procedure: first by using a probit model to analyze the consumption selection decisions, and thereafter an augmented Quadratic Almost Ideal Demand System (QUAIDS) model. We find that higher income, more education, and living in urban areas increase the usage of electricity while reducing the probability of using firewood. The estimated own-price elasticity for electricity is not significantly different from one, implying that electricity prices could be reduced to increase consumption without causing revenue loss to electricity utilities. However, the estimated income elasticities suggest that Ugandan households do not conform to the energy ladder theory but rather to the energy stacking practice, transitioning from firewood to charcoal, and eventually using an increased mix of energy types as household income increases. Therefore, the simple solution of reducing the electricity price alone may not increase electricity use and reduce the environmental and public health impacts related to firewood and charcoal usage. Addressing these externalities require a combination of targeted measures, including expanding the electricity grid to enhance electricity accessibility and supply reliability.

Paper 2 examines the factors determining the adoption and use of solar photovoltaic (PV) technologies in Uganda, using the Uganda 2018/2019 Living Standards Measurement Survey (LSMS) household data. The data is analyzed using Probit and Multivariate Probit models. The major drivers of solar PVs use are saving, education, age of household head, household size and income. Households in urban areas, households with access to grid electricity, households with reliable grid electricity supply, and female-headed households are less likely to adopt solar PVs. Given that most households in Uganda live below or around the poverty line, with limited ability to pay for solar panels, where in most cases the entire investment is up-front, the study recommends

that the government should establish credit schemes for solar provision to lessen the burden of upfront investment in solar PVs. The government should also promote the awareness of solar energy. Educating people, especially rural household heads, on clean solar energy's uses and benefits is also important. The government should encourage and support more research on solar PV technologies throughout the value chain to improve solar energy quality.

Paper 3 investigates how diesel prices affect charcoal prices in urban Uganda. Diesel is a vital component in the transportation of charcoal. Charcoal is a dominant energy source in urban areas of Uganda and increases in retail prices in the past have led to social unrest in the country. This paper assesses the relationship between charcoal prices and diesel prices to determine whether diesel prices influence the retail price of charcoal. We used an error correction model with monthly data for the period July 2010 through January 2021. As the variables are integrated of order zero and one, the ARDL bounds test is used. We find a long-term relationship between the retail price of charcoal and the supply price of charcoal and kerosene, which is a substitute energy source for the end users. The prices of firewood and diesel are not statistically significant in the model. The long-term equation includes a positive trend, indicating that the retail price of charcoal is increasing more over time than would be implied by the supply price of charcoal and the price of kerosene. Increasing demand from a growing urban population and reduced supply from deforestation are trends that will increase the equilibrium price of charcoal, which we observe.

Paper 4 reexamines the relationship between electricity consumption and economic growth in Uganda using quarterly data from 2010Q3–2023Q3. The time series for gross domestic product (GDP), capital stock, and electricity consumption are nonstationary. Using the Engle-Granger cointegration test, we do not find cointegration between GDP, capital stock, and electricity consumption, therefore we use a vector-autoregressive (Yavari & Mohseni) model in the analysis. From the Granger causality test, we find that there is no Granger causality from electricity to GDP, or vice versa, thus supporting the neutrality hypothesis. Previous studies of economic growth-electricity nexus, using data from before 2010, have found support for the feedback hypotheses where there is Granger causality in both directions between GDP and electricity consumption. We suggest that future research should focus on detecting any potential structural breaks in the GDP and electricity consumption relationship and what such a break may mean for economic growth and policy recommendations.

Norsk sammendrag

Avhandlingen er en samling av fire empiriske artikler om energirelaterte problemstillinger i Uganda. De gjelder etterspørsel etter elektrisitet, bruk av solceller, pris på trekull og sammenhengen mellom strømforbruk og økonomisk vekst.

Den første artikkelen handler om husholdningenes etterspørsel etter strøm i Uganda. Elektrisitetsbruken i Uganda er svært lav, med et gjennomsnittlig forbruk på 215 kWh per innbygger per år, mens det i gjennomsnitt for Afrikanske land sør for Sahara er 552 kWh per innbygger, og gjennomsnittet i verden er 2 975 KWh. Bare 15-20 % av husholdningene i Uganda tilgang til strømnettet samtidig som Uganda har ubrukt kraftproduksjonskapasitet. Ren energibruk sparer tid, beskytter brukernes helse og reduserer miljøforringelse. I artikkelen brukes data fra Uganda National Panel Survey (UNPS) for året 2018/2019. Data er analysert ved hjelp av modellen Quadratic Almost Ideal Demand System (QUAIDs). Jeg finner at elektrisitet er et substitutt for parafin, trekull og ved, ettersom modellens estimerte Hicksianske krysspriselastisiteter er positive. Den politiske implikasjonen av resultatene er at regjeringen kan bruke skatteinsentiver for å øke etterspørselen etter ren fornybar energi.

Artikkel 2 undersøker faktorer som bestemmer bruken av solcelleteknologier (PV) i Uganda. Data er husholdningsdata hentet fra Uganda 2018/2019 Living Standard Measurement Survey (LSMS). Data er analysert med en Probit-modell og en Multivariat Probit-modell. De viktigste faktorene som er korrelert med bruk av solcellepaneler i Uganda er sparing, utdanning, alder på husstandens overhode, husholdningens størrelse og formue. Husholdninger i urbane områder, husholdninger med tilgang til strømnettet, husholdninger med pålitelig strømforsyning fra nettet og husholdninger med mannlig leder har mindre sannsynlighet for å ta i bruk solcellepaneler. Gitt at de fleste husholdninger i Uganda lever under eller rundt fattigdomsgrensen, og dermed har begrenset evne til å betale for solcellepaneler siden i de fleste tilfeller hele investeringen er på forhånd, bør regjeringen etablere kredittordninger for å redusere byrden med forhåndsinvesteringer i solenergi, og gjøre den mer tilgjengelig for fattigere og kredittbegrensede husholdninger. Mer forskning om markedsinnovasjon av ulike solcellepaneler er også ønskelig for å redusere kostnadene for sluttbrukerne. Videre bør myndighetene opplyse folk, spesielt husholdninger på landsbygda, om bruken og fordelene til ren solenergi. Spesielt bør regjeringen oppmuntre og støtte mer forskning på solcelle-PV-teknologier gjennom hele verdikjeden.

Artikkel 3 undersøker om, og hvordan, dieselpriser påvirker trekullprisene i urbane områder i Uganda. Diesel utgjør er en stor del av kostnadene ved transport av trekull. Kull er en dominerende energikilde i Uganda, og økninger i utsalgsprisen for trekull har tidligere ført til sosial uro i landet. Vi brukte en feilrettingsmodel med månedlige data for perioden juli 2010 til og med januar 2021. Fordi variablene er integrert av orden null og en, bruker vi ARDL grensetest for kointegrasjon. Vi finner en langsiktig sammenheng mellom utsalgsprisen på trekull og tilbudsprisen på trekull og prisen på parafin, som er en alternativ energikilde for husholdninger. Prisene på ved og diesel er ikke statistisk signifikante i modellen. Den langsiktige modell ligningen inkluderer en positiv trend noe som indikerer at utsalgsprisen på trekull øker mer over tid enn det som skyldes endringer i tilbudsprisen på trekull og parafinprisen. Økende etterspørsel fra en voksende befolkning og redusert tilbud av trekull som en konsekvens av avskoging er trender som vil øke likevektsprisen på trekull.

I artikkel 4 undersøkes på nytt sammenhengen mellom strømforbruk og økonomisk vekst i Uganda ved å bruke kvartalsdata fra perioden 2010Q3–2023Q3. Tidsseriene for bruttonasjonalprodukt (BNP), kapital og strømforbruk er ikke-stasjonære. Ved å bruke Engle-Granger-kointegrasjonstesten finner vi ikke kointegrasjon mellom BNP, kapital og elektrisitetsforbruk, derfor bruker vi en vektor-autoregressiv (Yavari & Mohseni) modell i analysen. Fra Granger-kausalitetstesten finner vi at det ikke er noen Granger-årsakssammenheng fra elektrisitet til BNP, eller omvendt. Resultatene våre støtter nøytralitetshypotesen. Tidligere studier av sammenhengen mellom økonomisk vekst og elektrisitetsforbruk i Uganda har brukt data fra før 2010 og disse studiene har funnet støtte for tilbakemeldingshypotesene der det er Granger-årsakssammenheng i begge retninger mellom BNP og strømforbruk. Vi foreslår at fremtidig forskning bør fokusere på eventuelle strukturelle brudd i forholdet mellom BNP og elektrisitetsforbruk og hva et slikt brudd kan bety for økonomisk vekst, og for valg av politiske virkemidler.

1 Introduction

Energy is a vital component in increasing the production of goods and services. Without affordable, reliable, and clean energy, sustainable development cannot be achieved. Energy can be understood as a commodity, an input factor that frames an individual's capability set, thus, enabling his or her functioning in society (Beenstock, Goldin, & Nabot, 1999; Okyay, Aricioglu, & Yucel, 2014). Like many other economies, the energy sector is one of the key sectors of the economy of Uganda, as it enables the production of goods and services, supports livelihood through employment, provides revenues to the government through fuel taxes and enhances foreign exchange earnings from power exports. Uganda is classified as a developing country and one of the world's poorest nations, with a GDP per capita of US$ 822, and with 41.3% of its population living on less than US$1.90 a day in 2016 (World Bank, 2020).

The country is home to great lakes and rivers like the Nile basin, providing a great hydroelectricity generation potential. Located at the equator, Uganda is endowed with sunshine giving it a huge potential to generate solar electricity. However, the total energy consumption in Uganda was 0.083 Quad BTU in 2019 (Energy Information Administration, 2022), putting Uganda on a low energy consumption side. Uganda uses various energy resources, including hydropower, biomass, solar, geothermal, peat, and fossil fuels. Biomass energy constitutes about 90% of Uganda's energy use (Ministry of Energy and Mineral Development, 2015a). Charcoal is mainly used in urban areas for cooking purposes, while firewood, agro-residues and wood wastes are the primary energy sources in rural areas (Nzabona et al., 2021).

The high reliance on biomass in Uganda has led to high deforestation rates to meet the increasing demands for firewood and charcoal. Between 1990 to 2010, the forest area decreased from 49,240 km^2 to 29,880 km^2 (Energypedia, 2021). This about 39 % of the forest cover, was depleted in a decade. The rapid loss of forests has resulted in firewood scarcity and escalating charcoal prices. Moreover, burning biomass is responsible for high indoor air pollution levels that cause respiratory diseases. In addition, since much time is spent collecting wood fuel, people are deprived of the time to engage in income-generating activities, and children of study time. Therefore, there is a rationale for clean, renewable energy such as electricity from hydroelectricity, solar or wind.

Furthermore, in Uganda, only 15% of the households accessed electricity through the grid (National or mini-grid) in 2019, most of whom lived in urban areas (UBOS, 2019). Lack of access to electricity has severely constrained the economic development of Uganda, mostly in the rural areas, by hindering the establishment of businesses that require electric power and forcing companies to buy diesel or petrol generators that are costly to operate and negatively impact the environment. Besides, lack of electricity hinders access to information and communication technologies (e.g., mobile phones, computers, internet), isolating rural areas from the rest of the country.

Additionally, many households find electricity costly, both in terms of connection fees and the price of electricity (Blimpo & Cosgrove-Davies, 2019). Moreover, there are critical constraints related to electricity transmission. Many households, firms, and public agencies that would otherwise use electricity do not have access to supplies through the grid. Grid extension and maintenance are costly, thus areas without grid access are usually characterized by widely dispersed households. Notably, even when access to electricity is provided, rural take-up rates of grid electricity remain low. This is usually due to high connection fees, frequent outages of electricity and the availability of electricity substitutes. However, if the low electricity take-up is a demand-side constraint, it calls for a deeper understanding to come up with incentives to increase electricity take-up given its advantages over its substitutes.

However, off-grid solar energy has become a viable alternative to traditional electricity systems in Uganda. Like other renewables, it has significantly contributed to the global quest for power sector decarbonization. Solar energy has provided a suitable electrification alternative to many isolated rural areas, as the photovoltaic (PV) systems can be built small-scale and decentralized. However, in Uganda's rural areas, solar energy consumption is limited to lighting and charging phones. Therefore, ensuring access to solar energy to meet the demand for cooking and affordability issues remains a challenge throughout the country.

In urban areas, the most important source of energy for cooking is charcoal. Charcoal contributed approximately USD 26.8 million to Uganda's GDP in 2011 (Ministry of Energy and Mineral Development, 2015b). The charcoal industry employs wood producers, charcoal producers, transporters, and vendors. This implies the charcoal industry is a vital sector of the Ugandan economy. It is noticed that the Uganda's retail charcoal prices have been increasing since 2018.

There are many policies developed to govern energy sources to meet the country's energy needs for social and economic development in an environmentally sustainable manner. However, clean-modern energy sources remain expensive and unreliable, thus continued preference for charcoal since it is relatively cheaper.

There is increased electricity consumption in Uganda, and we observe that Uganda's annual GDP growth has been consistently positive since 1986. Could the increase in electricity consumption have led to increased economic growth? Though there exists vast literature examining the electricity consumption-economic growth nexus, there are mixed findings both in theoretical and empirical studies. Mawejje and Mawejje (2016), Sekantsi and Okot (2016), (Alinda et al., 2022) and (Mutumba et al., 2022), studied the relationship between electricity consumption and economic growth in Uganda and reported conflicting results. Sekantsi and Okot (2016), Alinda et al. (2022) and (Mutumba et al., 2022) find a bidirectional long-run relationship between electricity consumption and economic growth in Uganda while Mawejje and Mawejje (2016) and report a unidirectional causality from electricity consumption to economic growth in Uganda.

1.1 Research objectives

Given the above background, this research has drawn up four major objectives that will guide this thesis.

To analyze the household energy demand in Uganda by estimating the price and expenditure elasticities. We use the data on expenditure and prices of four energy groups (wood, kerosene, charcoal and electricity) and jointly estimate households' demand for these energy types using a Quadratic Almost Ideal Demand System (QUAIDS) by Banks et al. (1997). The research question is, how can we increase electricity consumption in Uganda to improve people's welfare? In this study, we estimate the income and price elasticities of household demand for energy fuels to find ways of increasing the demand and hence the usage of cleaner fuels, specifically electricity, at the household level.

To assess and empirically test which factors determine the adoption hence the usage of solar PV technologies in Uganda. This is done by employing binary probit and Multivariate probit models. We aim at exploring ways to increase electrification among Ugandans since the long-serving system of grid electricity has failed to solve the energy poverty problem in Uganda. The study is specific to Uganda to identify its uniqueness in terms of the drivers of solar PV adoption.

Third, it will assess the relationship between charcoal prices and diesel prices and other fuel types such as electricity and firewood in Uganda, using the Autoregressive distributed lag (ARDL) model. We hypothesize that an increase in diesel price led to high charcoal prices.

Fourth, it will examine the nexus between electricity consumption and economic growth in Uganda. The study employs the Vector Auto regressive (Yavari & Mohseni) model. Therefore, the paper aims at examining the type of causal relationship between electricity consumption and economic growth (no causality, unidirectional causality, or bi-directional causality).

1.2 Materials and Methods

1.2.1 Data

The thesis uses secondary data from two different sources: the Uganda Bureau of Statistics (UBOS), and the Electricity Regulatory Authority (ERA).

The first paper uses the UBOS' Uganda National Panel Survey 2018/2019 data - also known as Living Standards Measurement Study (LSMS) data. It is a nationally representative household survey, and it has information on topics that include household characteristics, energy and non-energy expenditures, as well as other socio-economic characteristics. The sampled households were stratified into four regions (Central, Northern, Western and Eastern), districts and enumeration areas. This data set is complemented by data on electricity prices from ERA. A detailed description of the data is provided in the paper.

The second paper uses LSMS data for 2018/2019.

The third paper uses time series monthly data from UBOS covering the period from July 2010 to January 2021. The data set includes prices of different energy types used in the calculation of Uganda's price index.

Finally, the fourth paper uses a data set obtained from UBOS. The quarterly data covers the period 2010Q3- 2023Q2. This data is complemented by data from ERA, showing the Electricity consumption in the country.

1.2.2 Methods

The thesis employs different statistical methods for the different papers._Paper 1 employs the Quadratic Almost Ideal Demand System (QUAIDS) developed by Banks, Blundell and Lewbel (1997), an extension of the Almost Ideal Demand System (AIDS) model developed by (Deaton & Muellbauer, 1980). The model is more flexible than the AIDS model because it allows demand curves to be nonlinear in the logarithm of income. The model is written below.

$$S_{jk} = \alpha_{jk} + \sum_{i=1}^{n} \gamma_{ij} \ln p_{ik} + \beta_j \ln\left[\frac{y_k}{a(p)}\right] + \frac{\lambda_j}{b(p)}\left[\ln\left(\frac{y_k}{a(p)}\right)\right]^2 \text{ for } j = 1,2,3,4 \quad (1)$$

where S_{jk} is the budget share for each energy type of the kth household of its total energy demand expenditures; k =1, ..., N denotes the sampled households; p_{ik} represents the price of energy type i for the kth household (consumer); y_k represents the total energy expenditures of the kth household; *a(p)* and *b(p)* are the translog price aggregator and Cobb-Douglas aggregator. α_{jk}, γ_{ij}, β_j and λ_j are the parameters to be estimated.

Excluding the quadratic term in equation (1) makes an AIDS model. Theoretically, the above equation must satisfy the laws of demand, which requires imposing the adding up condition, the homogeneity of degree zero in prices and income, and the symmetry conditions of the Slutsky parameters. To account for heterogeneity among households, we include household demographic variables which have been considered relevant in the literature, e.g., (Khanal, Mishra, & Keithly, 2016) found several variables to be significant in influencing a household's purchase decisions. Specifically, our QUAIDS model includes the age of the household head, household population size and marital status of the household. Some energy types have zero household expenditure due to non-preference, non-affordability, and non-availability, leading to the existence of corner solutions hence biased estimates (Park et al., 1996) . To solve the problem, we only consider enumeration areas with a probability of access to electricity greater than 0.1. This probability of access is a dividend of households connected to electricity to total households in an enumeration area. We note that unlike in the conventional system specification without censoring, the deterministic components do not add up to unit across all equations of the system, and so the error terms in the estimation form do not add up to zero (Yen, Kan, & Su, 2002). As a result, the usual procedure of imposing the adding-up restriction on the system and dropping one equation is not valid. We estimate the first stage using a probit model that describes the consumption selection decisions, and we use the augmented QUAIDS in the second stage. Finally, adopting the equation suggested by (Poi, 2012), we derive expenditures and Marshallian price elasticities from the compensated (Hicksian) price elasticities.

Paper 2 employs the binary probit model and multivariate probit (MVP) model to analyze the factors influencing the adoption of solar PVs in Uganda. Binary probit regression models are used to examine the relationship between a binary dependent variable y and one or more explanatory variables X. The dependent variable 'y' in this study represents the household's decision to purchase and use solar PV. ($y = 1$, adopt; $y = 0$, otherwise). The explanatory variables can take any form (discrete, continuous).

The binary regression is mathematically specified as:

$$y_i^* = \boldsymbol{\beta X_i} + \varepsilon_i \tag{2}$$

$$y_i = \begin{cases} 1 & \text{if } y_i^* > 0 \\ 0 & \text{if } y_i^* \leq 0 \end{cases} \tag{3}$$

y_i^* is a latent variable, y_i is the observed variable that takes on the value of 1 if a household *i* has a solar panel and zero otherwise. $\boldsymbol{X}$ is a vector of independent variables.

We also employ a Multivariate probit model. This model is the most appropriate for analyzing solar PVs adoption since we believe that solar PV adoption is correlated with grid electricity, kerosene, and other lighting forms. Therefore, we estimate the MVP model with four binary outcome choice variables: solar PVs, grid electricity, kerosene, and others (none of the mentioned three). Applying the equation suggested by Mullahy (2016), the multivariate probit model is formulated as:

$$y_{ij}^* = \boldsymbol{\beta_j X_{ij}} + \varepsilon_{ij} \tag{4}$$

$$y_{ij} = \begin{cases} 1 & \text{if } y_{ij}^* > 0 \\ 0 & \text{if } y_{ij}^* \leq 0 \end{cases} \tag{5}$$

In this model, y represents the four binary outcomes (lighting fuel choices): solar PVs, grid-electricity, kerosene, and others. For each type of lighting fuel choice, the household is faced with a binary choice (1 = use of the energy type, or 0 = otherwise). $i = 1,2,3 \ldots N$ indexes observations, while. $j = 1,2,3,4$ indexes outcomes. $\boldsymbol{X}$ is a matrix of the explanatory variables; $\beta_1, \beta_2, \beta_3$ *and* β_4

are parameter estimates and u_{ij} are the error terms assumed to be independent identically distributed across i but correlated across j for any i. The model is estimated using the maximum likelihood estimation.

Papers 3 and 4 aim at examining a long-run relationship between variables. We start by determining the stationarity properties of the univariate time series to avoid spurious regressions. We use the augmented Dickey-Fuller (ADF) to examine if the time series have a unit root.

The concept of cointegration was first introduced by Granger (1981) and has been applied and improved further by Engle and Granger (1987) Phillips and Ouliaris (1990) and Johansen (1991) among others. The Engle and Granger cointegration test requires that the time series, are nonstationary in levels but stationary in first differences. The first step for cointegration is to test whether each of the series is nonstationary or not. If nonstationary, we go to the second step to verify the long-run relationship between them. If a pair of series are cointegrated, then there must be Granger causality in at least one direction, which reflects the direction of influence between series.

Papers 3 employ the Autoregressive distributed lag (ARDL) approach. The advantage of the ARDL model is that, unlike the Johansen cointegration test, which is not applicable when variables have mixed order of integration, the ARDL model is applicable. The model also gives unbiased when the variables are of the same order of integration.

The empirical model is specified as follows:

$$\text{In}y_t = \alpha + \beta_1 In\boldsymbol{X}_t + \varepsilon_t \tag{6}$$

The variables are in natural logarithms. y_t is the dependent variable, and $\boldsymbol{X}_t$, is a vector of independent variables. We estimate an autoregressive distributed lag (ARDL) model in this paper because the model is the most appropriate when some variables are stationary at I(0) and others are not stationary. The ARDL model captures both the short-run and long-run effects of the independent variables on the dependent variable. The ARDL model is illustrated as follows:

$$\Delta\text{In}y_t = \beta_0 + \sum_{i=1}^{n} \beta_1 \Delta\text{In}y_{t-i} + \sum_{i=1}^{n} \beta_2 \Delta\text{In}\boldsymbol{X}_{t-i} + \beta_7 Iny_{t-1} + \beta_8 In\boldsymbol{X}_{t-1} + \varepsilon_t \tag{7}$$

Where Δ is the difference operator. In the first part of the equation $\beta_1 \ldots.\ \beta_k$ represents short-run dynamics of the model, and the second part $\beta_{k+1} \ldots.\ \beta_n$ represents long-run relationships. We conduct the ARDL bound test to check for the existence of cointegration. The null hypothesis (H_0) in the equation is $\beta_{k+1} = \cdots = \beta_n = 0$, which means the non-existence of a long-run relationship. If the F-statistics is greater than the upper critical bound (UCB), we reject the H_0 hence the existence of cointegration. However, if the F-statistics is less than the lower critical bound (LCB), accept the null of no cointegration. But if $LCB \leq \mathrm{F-statistics} \leq \mathrm{UCB}$, then the decision is inconclusive.

After finding the long-run relationship between variables, the study uses the error correction model (ECM) to find the short-run dynamics. The error correction model (ECM) for the estimation of the short-run relationships is formulated as follows:

$$\Delta \mathrm{In} y_t = \beta_0 + \sum_{i=1}^{n} \beta_1 \Delta \mathrm{In} y_{t-i} + \sum_{i=1}^{n} \beta_2 \Delta \mathrm{In} \boldsymbol{X}_{t-i} + \propto_1 ECT_{t-1} + \varepsilon_t \quad (8)$$

$\propto_1$ is the coefficient of the error correction term (ECT_{t-1}) and it must be negative and statistically significant, indicating that any long-run disequilibrium among the dependent and independent variables will converge back to the long-term equilibrium. It shows the speed of adjustment towards long-run equilibrium.

In case of no cointegration among variables, we estimate the ARDL short-run model as:

$$\Delta \mathrm{In} y_t = \beta_0 + \sum_{i=1}^{n} \beta_1 \Delta \mathrm{In} y_{t-i} + \sum_{i=1}^{n} \beta_2 \Delta \mathrm{In} \boldsymbol{X}_{t-i} + \varepsilon_t \quad (9)$$

The equation above estimates the short-run dynamics.

Paper 4 employs the vector autoregressive (Yavari & Mohseni) model. There is no cointegration between the variables of interest, therefore, the error correction models cannot be applicable, and the VAR model is appropriate.

1.3 Summary of findings

This section gives a summary and discussion of the results of each of the four papers.

1.3.1 Paper 1: Household energy demand in Uganda

Paper 1 investigates the elasticities of household demand for energy fuels to find ways of increasing the demand and hence the usage of electricity, at the household level.

We find that all the parameters of the household demographic attributes exhibit statistically significant values, implying that household energy demand depends on household characteristics.

The coefficients of log of income and log of income squared of fuel types are also significant implying a non-linear demand system hence the justification of the QUAIDS model. We find that in the short and medium-term, income growth leads to increased consumption of charcoal which is not the case in the remaining three fuel types. All own-price elasticities for energy types are negative, implying that the negativity condition is fulfilled and consistent with economic theory. We observe that, compared to uncompensated elasticities, some of the Hicksian cross-price elasticities have different signs, which further implies that the household income effect plays a significant role in energy demand. The results also indicate that electricity is a substitute for each of the other energy fuels (the cross elasticities are all positive). The cross elasticity between electricity and charcoal is the smallest, indicating that people are quite rigid to changing from charcoal to electricity. This correlation with electricity consumption suggests that manipulating the price of electricity through incentives could influence shifting households' energy mix itself.

1.3.2 Paper 2: Factors determining the use of solar PV technologies in Uganda.

Paper 2 aims at finding the determinants of solar PV adoption. The estimates from the probit model indicate that solar PVs' adoption in Uganda is driven by savings, education, age of the household head, household size, and wealth. We argue that households can afford to cover the up-front investment of solar PVs with savings. Education is likely to increases the purchasing power and awareness hence the preference for cleaner and more convenient energy sources like solar. In the case of a large household, the fixed cost of solar PVs can be spread among the household members. Also, older household heads may be richer and thus can afford to adopt solar PVs thus age positively affects solar adoption. Annual household income positively affects solar adoption due to affordability reasons. On the contrary, households in urban areas, households with access to grid electricity, households with reliable grid-electricity supply and male-headed households are less likely to adopt solar PVs. We argue that households already connected to the grid may be reluctant to adopt solar PVs because they may perceive solar adoption as an additional cost, and there may be a lock-in effect to grid electricity. We notice that urban households are already connected to grid electricity. Also, where grid electricity supply is reliable, the probability of adopting solar PVs reduces, an indication that grid electricity is preferred to solar energy. Regarding gender, women in Uganda are more responsible for energy collection; they are more affected by lack of energy. Hence, they may be more willing to pay for cleaner and more convenient energy technologies like solar PVs than the Male. Besides, males tend to be richer and are most probably already connected to grid electricity.

From the Multivariate Probit Model, the coefficients for location are negative and significant for solar, kerosene and others and positive for grid-electricity. This implies that urban households are more likely to adopt grid electricity than other energy sources. This may be explained by the fact that grid electricity is viewed as a better energy source in terms of voltage. Moreover, there is more access to grid electricity in urban areas than in rural areas. The effects of each variable on solar adoption shown by the Multivariate Probit model are similar those in the binary probit Model in terms of sign and significance.

1.3.3 Paper 3: The relationship between charcoal and Petrol prices in Uganda

In this paper, we investigate the relationship between diesel and charcoal prices. We employ the Augmented Dicky Fuller (ADF) and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests for stationarity, and the results revealed that charcoal, Diesel, and Kerosene-become stationary after the first difference, i.e., I(1). Whereas the firewood and supply price of charcoal, are stationary in levels; hence these two variables are I(0). Since the variables are of mixed order of integration, the ARDL technique is the most appropriate.

Using the bounds test of cointegration, we find cointegration between charcoal prices and all the other variables, i.e., there exists a long-term relationship between these prices. Indeed, we expected the long-term link between prices along a supply chain from source to retail as these prices adjust to reflect changing supply and demand conditions. There are not statistically significant autoregressive or distributed lag terms in the estimated model, reflecting a lack of short-term dynamics beyond the long-term equilibrium correction.

In the model, the trend variable has a statistically significant positive parameter. This may reflect increased demand, increased transportation costs, or both. We do not have access to any data that would allow us to clearly separate these two effects in the empirical model.

However, diesel prices are statistically insignificant in the empirical model. This implies an increase in transportation costs would reflect increases in the distance the charcoal is transported or increases in the transportation time, say, due to traffic congestion.

The results of the ARDL model show a long-term positive relationship between the retail prices of charcoal and kerosene. This positive relationship is as expected for two goods that are substitutes in consumption. The absence of a short-term link between kerosene and charcoal prices suggests that there is limited short-term substitution between charcoal and kerosene and that the substitution is related to the choice of cooking technology rather than the short-term choice of energy source.

1.3.4 Paper 4: Electricity consumption and economic growth nexus in Uganda

In this paper, the Augmented Dicky Fuller (ADF) for unit root test revealed that all variables were non-stationary, hence integrated of order one, i.e. I(1). There is no cointegration between the variables, therefore the appropriate model to use is the VAR model. We include a centered dummy variable for 2020 Q2 associated with the Covid-19 lockdown period that slowed economic activity in general, and investment and electricity consumption. Using Granger causality results, reveal that there is no Granger causality from electricity consumption to economic growth, or vice versa.

The results confirm the neutrality hypothesis of causality between economic growth and electricity consumption. The results contradict with those of (Sekantsi & Okot, 2016), who fund a bi-directional causality between Uganda's economic growth and electricity consumption. They also contradict the findings of (Mawejje & Mawejje, 2016), who found a unidirectional causality from electricity to GDP in Uganda.

1.4 Conceptual framework: energy dynamics in Uganda

The thesis examines energy consumption in Uganda with aim of improving social welfare. Particularly it seeks to increase electricity consumption, given its advantages of being a renewable, clean energy.

This conceptual framework captures the interplay of various factors across the papers, providing a holistic view of energy consumption in Uganda. It considers the macro-level influences, energy sources, household-level factors, and government interventions.

- Macro factors include: Economic growth, this influences overall energy consumption and production capacity. Population dynamics, these affect energy demand and infrastructure needs. Urbanization, this impacts energy distribution, access and consumption.
- Household level factors include: Income level which determines affordability and preference for different energy sources. Household age, education and size, which

influences the choice between traditional and modern energy solutions at the household level

- Government interventions include: Policy measures which directly impact energy access, affordability and sustainability. Incentives which encourage the adoption of renewable energy sources.

Economic development is included the macro factors. It includes Industrial growth which connects energy consumption to economic activities and development and infrastructure investment which influences the overall energy supply chain and distribution. Energy prices also affect the demand and supply of energy fuels.

Paper	Objective and research question	Methods	Data	Key findings
1	Analyze household energy demand	QUAIDS	LSMS 2019/2020	Unitary own price elasticity of electricity. Electricity is a substitute of other energy fuels. The positive cross elasticities between energy sources indicate the presence of the energy stacking.
2	Examine the factors determining the adoption of solar PV technologies in Uganda	Multivariate probit	LSMS 2019/2020	Households in urban areas prefer grid electricity to solar, kerosene and other energy sources.
3	Assess the relationship between charcoal prices, diesel prices and other fuel types	ARDL	UBOS Monthly data 2010-2021.	There is no causality between charcoal retail prices and diesel prices. The long-term equation includes a positive trend, indicating that the retail price of charcoal is increasing more over time. Increasing demand from a growing urban population and reduced supply from deforestation are trends that will increase the equilibrium price of charcoal.
4	Examine the nexus between electricity consumption and economic growth in Uganda.	VAR	UBOS quarterly 2010-2023.	There is no causality between economic growth and electricity consumption. The existence of a possible structural break in the growth pattern calls for further study on the topic.

Table 1: Snapshot of papers comprising the thesis

1.5 Conclusions and implications

Electricity is a clean, renewable energy, and we advocate for it due to its advantages over and above other fuel types like firewood which have high pollution capacity. From our study, we can conclude that higher incomes and living in urban areas increase the consumption of electricity. The unitary own price elasticity of electricity suggest that a price reduction will not significantly decrease the revenue of the electricity producers and distributors. Thus, a price reduction provides a win-win, or at least win–not–lose option, for the government, where households' welfare and economic development can be stimulated at a low or no cost.

The estimated income and cross elasticities suggest that Ugandan households do not conform to the energy ladder theory but rather to the energy stacking theory. In energy stacking theory, a mix of energy sources are used as income increases. The traditional fuels like charcoal, are used a long side modern ones like electricity.

Households in urban areas prefer grid electricity to solar, kerosene and other energy sources. This may imply that grid-electricity is of better quality, e.g., in terms of voltage than other energy sources. Moreover, solar PV units with higher voltage can be costly to buy, whereas with grid-electricity, there may be less of an up-front investment. The difference in the cost profile over time might be decisive for liquidity-constrained households. The government should educate people, primarily rural households, on the uses and benefits of clean solar energy. Education creates awareness of clean energy such as solar energy, thus increasing the adoption of solar. Therefore, the government, developmental institutions, and solar PVs dealers should undertake awareness campaigns for solar PVs adoption in Uganda. If possible, the government may enforce regulations on the quality of the PVs products and after-sales services provided by solar dealers. This is because the low-quality solar products and lack of after-sales services spoil the "goodwill" of solar PVs, hence, hindering their adoption.

The increase in the retail prices of charcoal is not due to increase in diesel price. It may be due increased urbanization or increased transportation costs due to traffic congestion but not the cost of diesel. There was no causality between charcoal retail prices and diesel prices. Therefore, improved forest management and replanting are important to maintain supply volume.

The evidence of no relationship between economic growth and electricity consumption in Uganda both in the long run and short run differ from the previous analysis by Mawejje and Mawejje (2016) who found support for the growth hypothesis, and Sekantsi and Okot (2016) and Alinda et al. (2022) found support for the feedback hypothesis. The difference could be based on the differences in time periods. The economy was growing rapidly until about 2011 and then settled at a slower growth rate. Previous studies used data from both periods without testing or controlling for a possible structural break in the growth pattern. The findings of no relationship between economic growth and electricity consumption indicate that policies and incentives to increase electricity consumption are not necessarily growth enhancing but might be welfare enhancing (reading lights, using mobile phones and replacing traditional fuels with electricity, among others).

Reference List

Alinda, K., Tumwine, S., Kaawaase, T., Navrud, S., Nalukenge, I., & Sserwanga, A. (2022). Evidence of Causality between Economic Growth and Electricity Consumption Expenditure in Uganda. *Journal of Energy Research and Reviews*, *10*(2), 1-18.

Banks, J., Blundell, R., & Lewbel, A. (1997). Quadratic Engel curves and consumer demand. *Review of Economics and statistics*, *79*(4), 527-539.

Banks, J., Blundell, R., Lewbel, A. J. R. o. E., & statistics. (1997). Quadratic Engel curves and consumer demand. *79*(4), 527-539.

Beenstock, M., Goldin, E., & Nabot, D. (1999). The demand for electricity in Israel. *Energy Economics*, *21*(2), 168-183.

Blimpo, P., Moussa, & Cosgrove-Davies, M. (2019). *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*. World Bank Publications.

Deaton, A., & Muellbauer, J. (1980). An almost ideal demand system. *The American economic review*, *70*(3), 312-326.

Energy Information Administration. (2022). *Uganda 2021 primary energy data in quadrillion Btu*. eia. https://www.eia.gov/international/overview/country/UGA

Energypedia. (2021). *Uganda energy Situation*. https://energypedia.info/wiki/Uganda_Energy_Situation#:~:text=Uganda%20currently%20has%20one%20of,average%3A%202%2C975%20per%20capita

Engle, R. F., & Granger, C. W. (1987). Co-integration and error correction: representation, estimation, and testing. *journal of the Econometric Society*, 251-276.

Granger, C. W. (1981). Some properties of time series data and their use in econometric model specification. *Journal of econometrics*, *16*(1), 121-130.

Johansen, S. (1991). Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. *journal of the Econometric Society*, 1551-1580.

Khanal, A. R., Mishra, A. K., & Keithly, W. (2016). Heterogeneity in food demand among rural Indian households: The role of demographics. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *64*(3), 517-544.

Mawejje, J., & Mawejje, D. N. (2016). Electricity consumption and sectoral output in Uganda: an empirical investigation. *Journal of Economic Structures*, *5*(1), 1-16.

Ministry of Energy and Mineral Development. (2015a). *Energy and Mineral Development Sector Plan 2015/16 – 2019/20*. http://npa.go.ug/wp-content/uploads/2018/01/Energy-Sector-Development-plan-Final.pdf

Ministry of Energy and Mineral Development. (2015b). *National Charcoal Survey for Uganda*

https://pfccparliament.go.ug/wp-content/uploads/2019/04/NationalCharcoalSurvey_FINAL.pdf

Mullahy, J. (2016). Estimation of multivariate probit models via bivariate probit. *The Stata Journal*, *16*(1), 37-51.

Mutumba, G. S., Otim, J., S.Watundu, Adaramola, M. S., & Odongo, T. (2022). Electricity consumption and economic growth in Uganda. In C. Nzila, N. Oluoch, A. Kiprop, R. Ramkat, & I. Kosgey (Eds.), *Advances in Phytochemistry, Textile and Renewable Energy Research for Industrial Growth* (pp. 275-285). CRC press.

Nzabona, A., Tuyiragize, R., Asiimwe, J. B., Kakuba, C., & Kisaakye, P. (2021). Urban Household Energy Use: Analyzing Correlates of Charcoal and Firewood Consumption in Kampala City, Uganda. *Journal of Environmental and Public Health*, *2021*.

Obeng, G. Y., & Evers, H.-D. (2010). Impacts of public solar PV electrification on rural micro-enterprises: The case of Ghana. *Energy for Sustainable Development*, *14*(3), 223-231.

Okyay, U., Aricioglu, E., & Yucel, F. (2014). Energy consumption and economic growth nexus: Evidence from developed countries in Europe. *International Journal of Energy Economics and Policy*, *4*(3), 411-419.

Park, J. L., Holcomb, R. B., Raper, K. C., & Capps Jr, O. (1996). A demand systems analysis of food commodities by US households segmented by income. *American journal of agricultural economics*, *78*(2), 290-300.

Phillips, P. C., & Ouliaris, S. (1990). Asymptotic properties of residual based tests for cointegration *journal of the Econometric Society*, 165-193.

Poi, B. P. (2012). Easy demand-system estimation with quaids. *The Stata Journal*, *12*(3), 433-446.

Sekantsi, L. P., & Okot, N. (2016). Electricity consumption–economic growth nexus in Uganda. *Energy Sources, Part B: Economics, Planning, and Policy*, *11*(12), 1144-1149.

UBOS. (2019). *Uganda Bureauof Statistics* (Statistical Abstract, Issue. U. B. o. Statistics.

World Bank. (2020). *Poverty headcount ratio at $1.90 a day (2011 PPP) (% of population) - Uganda*. https://data.worldbank.org/country/uganda?view=chart

Yavari, K., & Mohseni, R. (2012). Trade liberalization and economic growth: A case study of Iran. *Journal of Economic Policy Reform*, *15*(1), 13-23.

Yen, S. T., Kan, K., & Su, S.-J. (2002). Household demand for fats and oils: two-step estimation of a censored demand system. *Applied Economics*, *34*(14), 1799-1806.

Research Papers

Paper 1

Household energy demand in Uganda: Estimation and policy relevance

Grace Alinaitwe [a,b]

[a] School of Economics and Business, Norwegian University of Life Sciences, 1432 Ås, Norway;

[b] Department of Management Science, Makerere University Business School, Kampala, Uganda

Abstract

The generation capacity of electricity in Uganda is much higher than its current demand. Increasing electricity use at the household level provides an opportunity to improve welfare and avoid environmental and public health externalities of the dominant energy sources: firewood and charcoal. The Uganda Living Standards Measurement Study (LSMS) 2018/2019 household data is used to study price elasticities of different energy types. Price and income elasticities are derived through applying a two-stage procedure: first by using a probit model to analyze the consumption selection decisions, and thereafter an augmented Quadratic Almost Ideal Demand System (QUAIDS) model. We find that higher income, more education, and living in urban areas increase the usage of electricity while reducing the probability of using firewood. The estimated own-price elasticity for electricity is not significantly different from one, implying that electricity prices could be reduced to increase consumption without causing revenue loss to electricity utilities. Thus, a price reduction seems to provide a great option, for the government, where households' welfare and economic development can be stimulated at a low or no cost.

Keywords

Energy consumption, Energy substitution, Renewable energy, Fuel stacking

1 Introduction

Access to affordable electricity is crucial to the welfare of households and studies have demonstrated its importance in the economic development process (Beenstock, Goldin, & Nabot, 1999; Okyay, Aricioglu, & Yucel, 2014). Accessibility to affordable electricity can prevent environmental degradation by reducing the use of biofuels while also protecting human health, as indoor pollution is reduced. However, 13% of the world's population still lacks access to electricity, most of whom live in the Sub-Saharan Africa (IEA, 2019). In Uganda, only 15% of the households were connected to the electricity grid in 2020, the majority living in urban areas (Uganda Bureau of Statistics, 2020).

A puzzling fact is that many households that have access to the electricity grid are not connected and many of those connected use little electricity, in most cases only for lighting. Without electricity, households use other types of energy, typically firewood, charcoal, and kerosene, to meet their daily energy needs. UBOS (2014) data indicate that 75% of Ugandan households used kerosene for lighting, while 87% used firewood or charcoal for cooking. Only 14% of the households used electricity for lighting, while only 1% used it for cooking. However, Uganda has implemented several programs to improve the supply and accessibility of electricity in the country's rural areas, e.g., Uganda's Rural Electrification Project (REP). Uganda has also implemented the connection policy by UECCC, where the Government provides a free electricity connection, but the cost of the wiring is paid by the household. This is aimed at addressing the affordability barrier posed by the initial costs of acquiring an electricity connection. Uganda also has a policy that ensures that every customer in the domestic category has 15 units of power at the lifeline (subsidized) tariff of UGX 250 per unit (kWh). Furthermore, the Sustainable Development Goal calls for "affordable, reliable, sustainable and modern energy for all by 2030" aiming to promote accelerated access to clean energy for improved welfare and socio-economic transformation.

On the other hand, according to the Electricity Regulatory Authority (ERA), in 2019, the installed generation capacity was 1240 MW, while the total peak demand was 724 MW (ERA, 2020). From a social point of view, the mismatch between generation capacity and usage represents waste, since the water is run by idle hydropower plants without generating electricity. The unproduced power is factored into the energy tariff sustaining unaffordable tariffs. Excess capacity implies overinvestment with unnecessary recoverable costs. The unused capacity would if utilized increase people's welfare and spur economic development, while reducing environmental degradation and health hazards from indoor pollution.

When the supply capacity exceeds the demand, one expects the price to go down. However, electricity prices in Uganda are not determined in a market based on supply and demand. Project lenders and investors in plants expect a reasonable return that allows adequate risk-adjusted returns with a sufficient margin to withstand changes in external conditions. Therefore, the expected prices and dispatch conditions are specified in the Power Purchase Agreement (PPA) between the generating company and the government. The PPA specifies a framework for the dispatch of the plant and the power supply according to the generator's requirements, a mechanism which intends to ensure a reasonable return on the investment and allocation of risk between the parties. The argument for high prices is that if they were market-determined, it would be insufficient to finance the system and new investments (Blimpo & Cosgrove-Davies, 2019). The ERA also regularly adjusts tariffs based on a formula intended to reflect changes in costs.

There are important physical constraints related to electricity transmission. Many households, firms, and public agencies that would otherwise use electricity do not have access to electricity through the grid. Therefore, further expansion of the grid could contribute to increasing consumption of electricity. Moreover, off-grid solar power helped to increase the use of electricity. The use of solar power is expanding and the Uganda Living Standards Measurement Study (LSMS) data for 2019 / 2020 showed that 36% of Ugandan households use solar energy.

This article aims to investigate ways to increase electricity consumption. Generally, electricity consumption can be increased through the expansion of the transmission and distribution lines or by increasing demand among those already connected to the grid: household, industrial, or public sectors. This paper specifically focuses on electricity consumption among households already connected to the grid. Estimating price and income elasticities will give insights into the effects of lowering prices on electricity demand. Moreover, price elasticities are useful because energy utilities require this information to make dispatch decisions. In addition, the government can use these elasticities to assess the impact of subsidies on the welfare of households. We also analyze income elasticities that are relevant for predicting energy use. Studies have found that income must reach a certain level for households to use a new fuel type (Blimpo & Cosgrove-Davies, 2019; Ngui et al., 2011).

There is limited literature on changes in energy consumption due to changes in income and prices in Uganda, partly due to lack of extensive data on consumer purchases and income flow. Most studies in developing countries rely on general household surveys, which often lack detailed information about household purchases and prices (Deaton, 1988, 1997; Deaton & Grosh, 2000). We have prices from the UBOS, however there is spatial price differences which UBOS data does not reflect.

This paper uses detailed household data from the Uganda 2019/2020 Living Standards Measurement Survey (LSMS). Using data on expenditure and prices of four energy groups of interest, we jointly estimate households' demand for these energy types using a Quadratic, Almost Ideal Demand System (QUAIDS) developed by Banks, Blundell and Lewbel (1997).

The rest of the paper is organized as follows. Section 2 describes the energy system in Uganda, while Section 3 outlines the demand system model, the empirical strategy used, and the data used in the analysis. The results are presented and discussed in Section 4, and concluding remarks are given in Section 5.

2 Background of the study

2.1 The electricity sector in Uganda

Before 1997, the Uganda Electricity Board (UEB) was a vertically integrated utility, managing electricity generation, transmission, and distribution. After unbundling UEB, three cooperate entities emerged, all regulated by the Electricity Regulatory Authority (ERA), an independent body under the Electricity Act of 1999. The three electricity entities created are explained in detail below.

The Uganda Electricity Generation Company Limited (UEGCL), manages the electricity generation in the country. The installed electricity capacity in Uganda increased from 400 MW in 2000 to 1240 MW in 2020, of which 82% is hydropower (ERA, 2019). This is still low in per capita terms (IEA, 2021). Uganda has a generation mix of energy sources, i.e., hydro, thermal, cogeneration with bagasse and grid-connected solar. Generation is carried out by more than 20 government-owned companies, public-private partnerships, and private producers. ERA sets these companies' feed-in tariffs, and they vary from company to company.

The Uganda Electricity Transmission Company Limited (UETCL) manages electricity transmission, i.e., the country's main (high voltage) grid. It is a single operator and is owned by the government of Uganda. UETCL buys electricity in bulk from the generating companies and sells it in bulk to the distribution companies. In addition, it can import and export electricity**.** The grid connects power generation plants to load centers throughout the country and interconnections with neighboring countries. UETCL plays the role of a Transmission System Operator (TSO) hence conducting the system operations, which include the dispatch and control of the operation of generation plants and other facilities necessary for system stability, security, reliability, safety and efficient operations. UETCL coordinates the power supply system to obtain an instantaneous balance between generation and consumption. In addition, it is responsible for upgrading and expanding the national grid. UETCL has faced many challenges in expanding its grid: limited load (utilization) growth amidst the increasing generation capacity, a weak distribution infrastructure system (not owned by UETCL), and a lack of proper coordination with new independent power producers (IPPs).

The Uganda Electricity Distribution Company Limited (UEDCL) manages electricity distribution sector. This sector has many players, and the aim was to eliminate monopoly hence improving both efficiency and effectiveness, resulting in fair prices and consumer protection. There are currently nine distribution companies in Uganda, each serving different geographical areas. Following the liberalization of the sector, there has been a marked drop in energy losses, from 30% in 1999 to 16% in 2020, while the legally connected customer base has increased from 180 000 in 2001 to more than 1.6 million in 2020 (ERA, 2019).

2.2 Other energy sources

Uganda's population depends mainly on firewood or charcoal for domestic energy needs (Ojelel, 2015; Tabuti, Dhillion, & Lye, 2003). Firewood is used for household cooking and commercial activities such as making bricks, distilling spirits, preserving fish, cooking food in restaurants, and producing charcoal.

While generally available to most rural dwellers, firewood has its shortcomings. It is difficult to ignite, burns out quickly, and produces smoke and ash detrimental to human health. The firewood for domestic use is collected mainly by women and children. Collecting firewood is time-consuming. For example, in Soroti, where firewood supply is scarce, people travel long distances of about 7 km, hence spending many hours looking for firewood (Egeru, 2014). Furthermore, firewood harvested for commercial use by small-scale industries requires a large amount of wood that is often green, leading to the depletion of the stock.

Charcoal, another fuel alternative, is the cheapest option for cooking in urban areas, and its consumption is projected to rise as the urban population increases. However, charcoal production harms the environment because it consumes large volumes of wood and produces hazardous gases.

This heavy reliance on forests as a fuel source, especially due to widespread charcoal production, is not sustainable in the long run. People find charcoal and firewood less costly than electricity, but the reliance on firewood and charcoal leads to the depletion of forests, reducing economic welfare and growth over time.

Solar energy is another potential energy source. In this study, electricity refers to the electricity supply from the grid, including solar electricity connected and sold through the national grid. However, there are many consumers with decentralized solar panels. The LSMS 2018/2019 indicated that 36% of Ugandan households used solar energy. Many of these, use it for smaller tasks like charging mobile phones and limited lightening at night from small batteries charged during the day.

Other energy sources used in the county include gasoline for vehicles, kerosene (paraffin) for lighting and cooking, and Liquefied Petroleum Gas (LPG) for cooking.

2.3 The energy ladder and energy stacking hypotheses.

In analyzing our results, we will utilize the *energy ladder* hypothesis, which postulates that households shift from traditional biofuels to more modern and efficient cooking fuels such as kerosene, LPG, and electricity as income increases. The energy ladder has solid fuels like firewood and charcoal at the bottom, non-solid fuels like gas and kerosene in the middle, and electricity at the top (Leach, 1992). Although many empirical studies found evidence for the energy ladder for example Behera, Ali and Marenya (2017), Behera, Jeetendra and Ali (2015), we observe that most households in Uganda still use fuels such as firewood, charcoal and kerosene as primary energy sources for cooking and lighting.

In contrast to the energy ladder hypothesis, the *energy stacking* hypothesis postulates that when a household's income rises, the household adopts modern fuels alongside traditional ones, as illustrated in Figure 1. In other words, traditional fuels are not abandoned completely but rather are simultaneously used alongside modern ones. Several studies have provided empirical evidence for the energy stacking hypothesis (Masera, Saatkamp, & Kammen, 2000; Ruiz-Mercado & Masera, 2015).

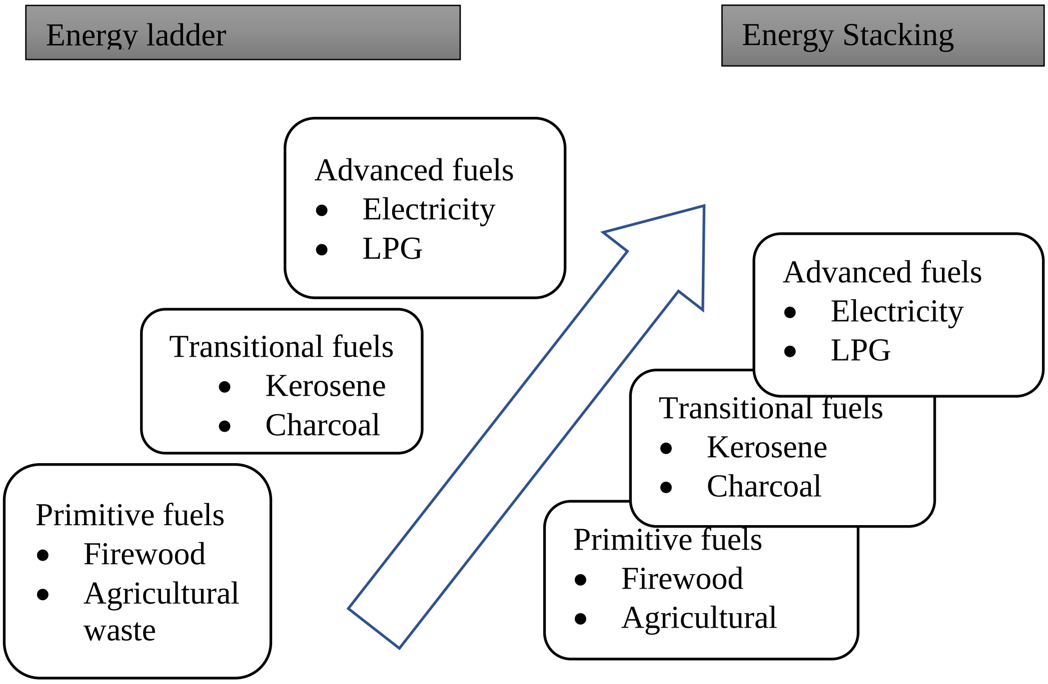


Figure 1: Energy ladder and Energy stacking

3 Methods and Data

3.1 Demand system

We follow a standard consumer theory approach, in which the amount of each type of energy consumed is a function of the prices of all commodities consumed and household income (Deaton, 1990). To estimate demand elasticities, we assume that consumers have convex preferences hence a quasi-concave utility function. The four energy types are firewood, charcoal, kerosene and electricity.

3.1.1 Separability

Assuming *n* goods, the unconditional demand function of good *i*, q_i is:

$$q_i = f_i(p_1, p_2, \dots, p_n, y) \qquad (1)$$

where p_i is the price per unit of good *i* and y is the income measured as a total expenditure. We can allocate the income into two weakly separable groups: group ***A*** consisting of *m* energy goods and group ***B*** consisting of the rest of the goods (non-energy goods). This implies that any price change of any good in group B affects the energy types in group A similarly.

The expenditure for group ***A*** (y_A) is allocated between the energy fuel types. This gives the conditional demand functions:

$$q_j = g_j(p_{A1}, p_{A2}, \dots, p_{Am}, y_A) \quad (2)$$

where $j = firewood, charcoal, kerosene, electricity$.

3.1.2 Quadratic Almost Ideal Demand System (QUAIDS)

The concept of Quadratic Almost Ideal Demand System (QUAIDS) was developed by Banks, Blundell and Lewbel (1997) and is an extension of the Almost Ideal Demand System (AIDS) model developed by Deaton (1997) and Deaton and Muellbauer (1980). This type of demand system is more flexible than usual AIDS because it allows demand curves to be nonlinear in the logarithm of income.

Many researchers, including Abdulai (2002), and Khanal, Mishra and Keithly (2016), have applied the QUAIDS model. The QUAIDS model is generally derived from an indirect utility function:

$$lnV(p, y) = \left(\left(\frac{lny - lna(p)}{b(p)} \right)^{-1} + \lambda(p) \right)^{-1} \quad (3)$$

where *y* is household expenditure on energy, ***p*** is the price vector, and *a(p)* is the trans-log price aggregator expressed as:

$$a(p) = \alpha_0 + \sum_{j=1}^{n} \alpha_j lnp_j + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \gamma_{ij} lnp_i lnp_j \quad (4)$$

with $j = 1,2,3,4$ and $i = 1,2,3,4$ for energy fuel types (wood, charcoal, kerosene, electricity):

$$b(p) = \beta_0 \prod_{j=1}^{n} p_j^{\beta_j} \quad (5)$$

where *b(p)* is a Cobb-Douglas aggregator. The term $\lambda(p) = \sum_{j=1}^{n} \lambda_j \ln p_j$ is a differentiable, homogenous function of degree zero in prices, and where $\sum_{j=1}^{n} \lambda_j = 0$

By applying Roy's identity to equation (1), we can derive the expenditure share of the QUAIDS model:

$$S_{jk} = \alpha_{jk} + \sum_{i=1}^{n} \gamma_{ij} lnp_{ik} + \beta_j ln\left[\frac{y_k}{a(p)}\right] + \frac{\lambda_j}{b(p)} \left[ln\left(\frac{y_k}{a(p)}\right) \right]^2 \quad (6)$$

where S_{jk} is the budget share for each energy type of the k^{th} household in its total energy demand expenditures; p_{ik} represents the price of energy *i* of the k^{th} household; y_k represents the total energy expenditures of the k^{th} household; *a(p)* and *b(p)* are described above. α_{jk}, γ_{ij}, β_j and λ_j are the parameters to be estimated.

Excluding the quadratic term in equation (4) reduces the expenditure shares to those from an AIDS model. The system of expenditure shares must satisfy the requirements of a valid demand system, which means imposing the adding up condition, the homogeneity of degree zero property in prices and income, and the symmetry conditions of the Slutsky parameters, which results in the following restrictions of the QUAIDS model:

$\sum_j \alpha_{jk} = 1, \sum_j \beta_j = 0, \sum_i \gamma_{ij} = 0, \sum_j \gamma_{ij} = 0, \sum_j \lambda_j = 0$ and $\gamma_{ij} = \gamma_{ji}$

3.1.3 Scaling

We include household demographic variables in the QUAIDS model to account for household heterogeneity. The following demographic characteristics have been considered in our model: age of the household head, household size, marital status, and education of the household head. These variables were considered by Heltberg (2004), Khanal, Mishra and Keithly (2016) among others and found to significantly influence a household's purchase decisions.

Urban households strongly prefer clean energy sources, given their poorer access to firewood and lack of space for lighting fires. Moreover, we expect the bandwagon effect to influence urban households to use electricity. Therefore, we expect a positive relationship between the variable urban and electricity.

We hypothesize that household size positively impacts gathering wood for fuel due to the increased labor supply for firewood collection (Dewees, 1989; Heltberg, Arndt, & Sekhar, 2000; Nepal, Nepal, & Grimsrud, 2011). Its impact on the probability of choosing clean cooking fuel is expected to be negative (Pandey & Chaubal, 2011). The education level of household members affects household energy choices through improved income. Educated people may have better-paying jobs and therefore have a higher opportunity cost for their time doing household chores. They readily adopt any time-saving device, which in most cases requires electricity. Education also directly increases knowledge and affects preferences for cleaner energy sources. Therefore, we hypothesize a positive relationship between the education of the household head and electricity (Gregory & Stern, 2014; Heltberg, 2004).

To assess the effect of household characteristics on energy demand, we use R. J. J. o. P. E. Ray (1983)'s model specified below:

$$e(p, z, \mu) = y_0(p, z, \mu) * e^R(p, \mu) \qquad (7)$$

z is a vector of s household characteristics, with the first term $y_0(p, z, \mu)$, scaling the expenditure function to control for household demographics characteristics and the last term

$e^R(p, \mu)$ represents the expenditure function of a reference household[1]. The scaling function is further decomposed into two components.

$$y_0(p, z, \mu) = \bar{y}_0(z) * \phi(p, z, \mu) \quad (8)$$

The first term measures the increase of household expenditure as a function of z, irrespective of the consumption patterns. For example, a household with three members will incur higher expenditures than one with one member. The second term accounts for the changes in the relative prices of the type of energy consumed and the actual energy consumed, subject to household composition. For example, a house of two adults and three infants will require different energy types than one of five adults.

R. Ray (1983) (R. Ray, 1983)and Poi (2012) suggested a parameterized QUAIDS:

$$\bar{y}_0(z) = 1 + \rho' z \quad (9)$$

and

$$ln\phi(p, z, \mu) = \frac{\prod_{j=1}^{k} p_j^{\beta_j} (\prod_{j=1}^{k} p_j^{\eta'_j z} - 1)}{\frac{1}{\mu} - \sum_{j=1}^{k} \lambda_j ln p_j} \quad (10)$$

with ρ being a vector of parameters to be estimated and η_j representing the j[th] column of the $s*k$ parameter matrix η. Therefore, incorporating demographics into the expenditure share, equation 4 becomes:

$$S_{jk} = \alpha_{jk} + \sum_{i=1}^{n} \gamma_{ij} ln p_{ik} + (\beta_j + \eta'_j z) ln \left[\frac{y_k}{\bar{y}_0(z) a(p)}\right] + \frac{\lambda_j}{b(p) c(p, z)} \left[ln\left(\frac{y_k}{\bar{y}_0(z) a(p)}\right)\right]^2 \quad (11)$$

where $c(p, z) = \prod_{j=1}^{k} p_j^{\eta'_j z}$ and $\sum_j \eta_{rj} = 0$ for $r = 1, \dots, s$

Where s are the household characteristics making the z vector. Once again, if $\lambda_j = 0$ for all j, then we have an AIDS model with demographics.

3.1.4 Censored data

Many households do not use all energy types, which leads to corner solutions. Zero expenditure values could be due to non-preference, non-affordability, or non-availability. Failure to account for these missing values in the estimation procedures could lead to biased estimates (Me-Nsope

[1] The reference household is one that contains only a single adult.

& Staatz, 2016; Park et al., 1996). To handle this problem, we first consider a household with a probability of access to electricity greater than 0.1. Probability of access to electricity is calculated as a fraction of connected households to total number of households in an enumeration area. We assume that the household makes energy consumptions decisions in a two-stages, first choosing which fuels to use and then the quantity to use of the selected fuels:

$$d_{jk}^{*} = Z_{jk}'\theta_j + Y_{jk}'\psi_j + v_{jk} \quad (12)$$

$$d_{jk} = \begin{cases} 1 & if \quad d_{jk}^{*} > 0 \\ 0 & if \quad d_{jk}^{*} \leq 0 \end{cases} \quad (13)$$

$$S_{jk}^{*} = \widehat{\Phi} s_{jk} + \theta_{jk}\widehat{\phi} \quad (14)$$

$$S_{jk} = d_{jk}S_{jk}^{*} \quad (16)$$

with j and k being the energy type consumed and household indices, respectively, while y and z are the vectors of the exogenous covariates, S_{jk}^{*} and d_{jk}^{*} are unobserved household budget shares and latent discrete choice decision variables, respectively; and finally S_{jk} and d_{jk} are the observed dependent variables for household fuel consumption and non-consumption counterparts. In this process, in the first stage, households decide whether to purchase each energy type and then decide how much to spend on each type in the second stage, conditional on a positive purchase decision from the first stage. We estimate the first stage using a probit model describing consumption selection decisions. The predicted estimates from the first stage are used to generate a cumulative distribution function (CDF), $\widehat{\Phi}()$. $\widehat{\phi}()$ are required to estimate the second- stage augmented QUAIDS in equation (11). We note that unlike in the conventional system specification without censoring, the deterministic components on the right-hand side of equation (13) do not add up to unity across all equations of the system. Thus, the error terms in the estimation form do not add up to zero (Yen, Kan, & Su, 2002). As a result, the usual procedure of imposing the adding-up restriction on the system and dropping one equation is not applicable. Therefore, with censoring, equation (8) is correctly estimated using the entire set of n equations (Yen, Kan, & Su, 2002).

3.1.5 Elasticities

Following an approach similar to that used by Poi (2012), we use equations (8)-(13) to derive expenditures and price elasticities by differentiating equation (12) with respect to $\ln y_k$ and $\ln p_{jk}$. Thus, the uncompensated price elasticity of fuel i with respect to the price changes of fuel j is given as:

$$e_{ij}^{m} = -\delta_{ji} + \frac{1}{S_{jk}^{*}}\left(\Phi_j\left(\gamma_{ij} - \left[\beta_j + \eta' z + \frac{2\lambda_j}{b(p)c(p,z)} ln\left[\frac{y_k}{\bar{y}_0(z)a(p)}\right]\right] * \left(\alpha_j + \sum_{n=1}^{N} \gamma_{jn} ln p_n\right) - \frac{\left(\beta_j + \eta_j' z\right)\lambda_j}{b(p)c(p,z)}\left(ln\left[\frac{y_k}{\bar{y}_0(z)a(p)}\right]\right)^2\right) + \theta_j\right) \tag{17}$$

where δ_{ji} is the Kronecker function. i.e $\delta_{ji} = \begin{cases} 1 & \text{if } j=i \\ 0 & \text{otherwise} \end{cases}$

Expenditure elasticity for good j is given as:

$$\sigma_j = 1 + \frac{1}{S_{jk}^{*}}\left(\Phi_j\left[\beta_j + \eta' z + \frac{2\lambda_j}{b(p)c(p,z)} ln\left[\frac{y_k}{\bar{y}_0(z)a(p)}\right]\right] + \theta_j\right) \tag{18}$$

Lastly, from expenditure and Marshallian price elasticities above, we can derive the compensated (Hicksian) price elasticities as

$$e_{ij}^{h} = e_{ij}^{m} + \eta_j S_{jk}^{*}. \tag{19}$$

3.2 Data

We use the Uganda National Panel Survey 2018/2019 data. This is a nationally representative household survey, with information on household characteristics, energy and non-energy expenditures, and other socio-economic characteristics. The sampled households were stratified into four regions (Central, Northern, Western and Eastern), districts and enumeration areas. We used expenditure data to proxy income, specifically the expenditure on fuel types, following the separability assumption described in section *3.1.1* above. In the cases where the quantity consumed was not reported, it was calculated by dividing expenditure by the reported unit price. Electricity price was not available in the survey, so the unit price was extracted from the website of the Electricity Regulatory Authority as reported by each distributor in their supply regions.

Kerosene price was reported in various consumption units and were standardized into liters and cost per liter consumed. Firewood also had various measurements, which we converted into bundles consumed and cost per bundle. Similarly, the survey reported units of charcoal consumption in bags of different sizes with different weights. These too were standardized into kilograms and the cost per kilogram.

The measurement errors of unit values are minimized by including household characteristics (control variables), including household size and the education of the household head, among others in the regressions. In addition, (Cox & Wohlgenant, 1986) suggested that households in the same region face the same prices, and as a result, urban dummy variable is included in the regressions.

For zero-consuming households, imputed prices based on the average fuel price for their enumeration area were assigned.

The constructed energy expenditure shares (expenditure on a particular energy fuel divided by total expenditure on all energy fuels) were used as the dependent variables for all energy types. Independent variables included: the logs of per unit prices of the energy types, income, income squared, and household control variables: a dummy for urban, household size, age of household head, a dummy for marriage, education level of the household head, and a dummy for the sex of the household head. Estimates for energy shares were obtained using the QUAIDS model (equation 15). A few households have access to electricity, most living in urban areas. It is impossible to determine if the household does not consume electricity by choice or by exclusion since the survey did not include information on the availability of electricity networks in the area. Therefore, in our study, we considered only enumeration areas with a probability of access greater than 0.1calculated as described below. We also included all households connected to the national grid even when they belonged to enumeration areas with less than 0.1 probability. The probability of access to an enumeration area was constructed by dividing the number of households connected to the grid by the total number of households in that enumeration area.

During data cleaning some households were eliminated due to the lack of basic information on household energy expenditure or lacked access to electricity.

4 Results and Discussion

In this section, we will present the descriptive statistics, results from the probit model, and the results from the QUAIDS model.

Figure 2 shows the cumulative probability of access to electricity using the whole data set before data cleaning of 2,571 households. We observe that 41 percent of the enumeration areas never had access to grid electricity. Considering enumeration areas with access, we were left with a sample of 687 households in our analysis.

4.1 Descriptive statistics

From Figure 2, we observe that 41% of the enumeration areas have no access to electricity, hence the need for censoring the data.

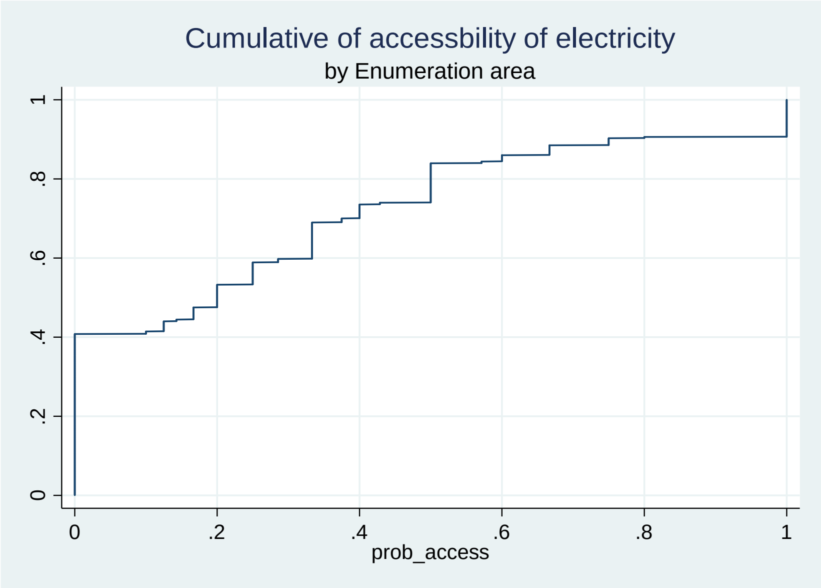


Figure 2: Cumulative distribution functions for electricity.

Table 1 shows the expenditure on different energy sources as a share of the total expenditure on energy. We observe that most households spend an average of 43% of their total energy expenditure on charcoal. Charcoal is the main energy source for cooking in the urban areas. Households spend an average of 23% on electricity. The least energy expenditure is firewood. This is because we mainly consider households with access to electricity. Using this sample, the finding could imply that the majority prefer other energy fuels to firewood, however using the whole data set, majority of the households still use firewood to cook.

Table 1: Expenditure on different energy sources as a share of total energy expenditure (n=687).

Variable	Mean	Standard Deviation
Firewood	0.07	0.20
Kerosene	0.27	0.38
Charcoal	0.43	0.38
Electricity	0.23	0.31

Table 2 shows some key descriptive statistics of the households. 76% of the households in our sample lived in urban areas. This is where most distribution grid lines are well developed. On average, the electricity price was UGX 529/kWh with a standard deviation of UGX 19.16/kWh. The average household size was 5 people. Males headed 65% of the households. The married were 66% of the sample, and on average, the household heads had spent an average of 8 years of schooling.

On average, households spent UGX 38 609 on energy. 26% of the households used firewood, 67% used charcoal, 61% used kerosene, and 43% used electricity from the grid.

Table 2: Descriptive statistics of the data.

Variable	Mean	Std. Dev.	Min	Max
Urban (1=urban)	0.76	0.43	0	1
Age of household head (years)	44.08	15.43	15	105
Household size (number)	5.29	3.04	1	23
Gender (1=male)	0.65	0.48	0	1
Education level of household head (year of schooling)	8.06	5.27	0	16
Married (share)	0.66	0.47	0	1
Electricity price (per kWh)	529	19.16	509	570.3
Charcoal price	675	70.85	600	800
Kerosene price	2108	124	1650	2300
Firewood price	630	107	571	1000
Total energy expenditure	38609	38656	500	348032
Firewood use (share)	0.16	0.34	0	1
Charcoal use (share)	0.67	0.47	0	1
Kerosene use (share)	0.61	0.48	0	1
Electricity use (share)	0.43	0.49	0	1

4.2 Regression results

The results in Table 3 show that urban dwellers are more likely to use electricity and less likely to use other fuel types. This may be because electricity accessibility is good in urban areas.

We also observe that male-headed households have a higher probability of electricity usage. This may be due to affordability since on average Ugandan males relatively have better incomes than women.

Being married increases the probability of using electricity. This could be due to the fact married people gain a more sense of responsibility once they start a family.

Table 3: Results from the first stage probit model on factors influencing the energy choice.

	Firewood	Kerosene	Charcoal	Electricity
Household-size	0.07	-0.03	-0.01	0.06
	(0.05)	(0.04)	(0.04)	(0.04)
Urban (0=rural)	-0.10	-0.95	-0.96	0.72
	(0.15)	(0.14)	(0.12)	(0.13)
Age of household head	-0.06	0.01	-0.02	0.02
	(0.03)	(0.02)	(0.02)	(0.02)
Marriage (1=married household	0.62	0.04	0.16	0.06
head)	(0.19)	(0.14)	(0.16)	(0.14)
Gender(1=male)	-0.31	-0.08	-0.42	0.03
	(0.16)	(0.13)	(0.16)	(0.13)

Table 4 provides estimated parameters of QUAIDS models on the price (of each energy type), household income (and its quadratic form), as well as a set of household demographics. The coefficients of the income (β_j) and income squared (λ_j) of fuel types are statistically significant, with a positive coefficient of income for charcoal (0.075). In the long run, an increase in income increases electricity consumption since the coefficient of income squared (0.005) is positive and significant. Increase in income reduces the consumption of firewood.

Table 4 indicates that most parameters of the household demographic attributes exhibit statistically significant coefficients, which implies that household energy demand depends on household characteristics. We observe that electricity consumption in urban areas is 10% higher compared to non-urban (rural) areas. On the other hand, firewood consumption in urban areas is 16% lower than that in non-urban. Therefore, these results can be an input to policies that encourage urbanization.

A one-year increase in education, increases electricity usage by 0.1%, while it reduces the use of firewood, kerosene and charcoal. Therefore, policies that encourage more education will help reduce the usage of non-renewable unclean energy types. Consequently, the results support more education for all households. As the quality improves, the demand of each energy fuel increases as indicated by d_j

Table 4: QUAIDS results of the four fuel types.

VARIABLE	Firewood Coefficient	charcoal Coefficient	Kerosene Coefficient	electricity Coefficient
Alpha (α_j)	-0.520***	0.949***	-0.207*	0.571**
	(0.158	(0.056)	(0.113)	(0.224)
Beta (β_j)	-0.053*	0.075***	-0.020*	-0.065***
	(0.029)	(0.022)	(0.010)	(0.025)
Gamma (γ_{1j})	-0.038	0.008	0.020*	-0.025**
	(0.025)	(0.007)	(0.010)	(0.012)
Gamma (γ_{2j}	0.008	-0.009**	-0.005	0.010
	(0.007)	(0.004)	(0.005)	(0.007)
Gamma (γ_{3j})	0.020*	-0.005	-0.002	-0.000
	(0.010)	(0.005)	(0.011)	(0.013)
Gamma (γ_{4j})	-0.025**	0.010	-0.000	-0.006
	(0.012)	(0.007)	(0.013)	(0.041)
Lamda (λ_j)	0.006***	0.001	-0.005***	0.005***
	(0.002)	(0.001)	(0.002)	(0.002)
Household size (number)	0.040***	-0.009***	-0.006***	-0.001
	(0.004)	(0.035)	(0.001)	(0.002)
Education (years of schooling)	-0.004*	-0.003***	-0.002*	0.001
	(0.002)	(0.001)	(0.001)	(0.001)
Urban (1=urban)	-0.155***	-0.285***	0.363***	0.097***
	(0.029)	(0.014)	(0.018)	(0.021)
Marriage (1=married)	0.304***	-0.049***	0.042***	-0.051***
	(0.035)	(0.008)	(0.008)	(0.011)
d_j	0.180***	0.285***	0.435***	0.117***
	(0.049)	(0.034)	(0.017)	(0.027)

*Note: The figures in parentheses are the standard deviations. *** p<0.01, ** p<0.05, * p<0.1 for* $j =$ 1,2,3,4. *Energy sources: 1=wood, 2=kerosene 3=charcoal 4=electricity.* β_j *is the coefficients of the income, and* λ_j *is the coefficient of income squared,* γ_{1j} *is the coefficient of fuel types j on firewood,* γ_{2j} *is the coefficient of fuel types j on charcoal, ,* γ_{3j} *is the coefficient of fuel types j on kerosene,* γ_{4j} *is the coefficient of fuel types j on electricity,* d_j *is the coefficient to indicate quality change.*

4.3 Expenditure elasticities

The expenditure[2] (income) elasticities obtained from the estimated QUAIDS model are reported in Table 5. The estimates for each energy type are statistically significant at a 1%

[2] We also note that all the estimated expenditure elasticities are conditional in the way that they represent the response of households' demand to a particular energy fuel due to changes in total energy expenditures.

level. The high elasticity of charcoal indicates that charcoal is more income elastic compared to the other fuel types. Hence households consume more charcoal as income increases. This could also indicate that they are reluctant to move from charcoal to electricity. Households seem to prefer charcoal for cooking even when their incomes improve. This indicates energy stacking whereby households rely on multiple fuels to meet their energy demands. The "primitive" fuels are maintained as income increases. Typically, better-off households use charcoal for cooking and electricity for lighting.

Table 5: Expenditure/income elasticities of the four fuel types.

Fuel type	Estimated coefficient	Standard error
Firewood	0.71	0.01
Charcoal	1.24	0.01
Kerosene	0.94	0.02
Electricity	0.74	0.10

We also note that all the estimated expenditure elasticities are conditional in the way that they represent the response of households' demand to a particular energy fuel due to changes in total energy expenditures.

4.4 Price elasticities

All Marshallian (uncompensated) and Hicksian (compensated) price elasticity estimates are computed at the sample mean and reported in Table 6. All own-price elasticities for energy types are negative. This implies that the negativity condition is fulfilled and hence consistent with the economic theory of demand, which states that when the price of a certain commodity increases, its demand decreases. We also observe that, compared to uncompensated elasticities, some of the Hicksian cross-price elasticities have different signs, which implies that household income effects play a significant role in energy demand. A negative cross-price elasticity means that the two energy fuels are complements, while a positive cross-price elasticity indicates that the energy types are substitutes.

4.4.1 Marshallian (uncompensated) elasticities

First, we analyze the Marshallian price elasticities because it is what is observed when a price changes. The own- price elasticities are negative, and they range between -1.26 and -0.88. They, indicate that as price increases, the own demand for that energy type decreases.

In Uganda, the main energy source used for cooking is firewood and charcoal. Also, kerosene is used in small cooking stoves, especially in urban areas. Very few households use electricity for cooking. The primary fuel used for lighting is kerosene and electricity. Since electricity can be used for both purposes (cooking and lighting), it has limited substitution possibilities.

A cross elasticity between firewood and electricity of -0.27 indicates that firewood complements electricity.

The negative cross-price elasticity (-0.21) also indicates that kerosene is a complement to charcoal. While kerosene is used for lighting, charcoal is mainly used for cooking purposes. The results also indicate that kerosene is a substitute for electricity (0.27), as both are used for lighting purposes.

Charcoal is a complement to all fuel types. Charcoal is mainly and almost exclusively used for cooking, hence complementing electricity and kerosene, which are used mainly for lighting. These result support the energy stacking theory where households use a mix of energy fuels. Charcoal also complements firewood, especially during seasons when firewood cannot be collected due to heavy rainfall and other factors like the sickness of the one who collects it in a household.

The Marshallian results indicate that electricity substitutes firewood and kerosene while complementing charcoal. Households seem to be reluctant to switch from charcoal to electricity for cooking purposes because of their cooking habits, cultures, and preferences. For example, when cooking the traditional food called *matooke* (cooked bananas), one must leave it on fire for a whole day. Besides, there are other underlying heavy costs of buying a cooker, and other appliances required in cooking while using electricity. This negative cross elasticity between electricity and charcoal is also in support of energy stacking theory.

4.4.2 Hicksian (compensated) elasticities.

The Hicksian price elasticities are also reported in Table 6 and can be used to reflect substitution effects in the elasticities. Considering the Hicksian results, we find that electricity has its own price elasticity of −0.6, which is lower than that of Marshallian (-0.88). This indicates the presence of the substitution effect of changes in prices and income.

The results show that electricity is a substitute for each of the other energy fuels since the cross elasticities are all positive, as seen in Table 6 above. The significant correlations between electricity consumption and other fuel types suggest that changing the price of electricity would influence shifting households' energy mix.

Table 6: Marshallian (uncompensated) price elasticities and Hicksian (compensated) price elasticities

	Marshallian Price elasticities				**Hicksian Price elasticities**			
	Wood	Kerosene	Charcoal	Electricity	Wood	Kerosene	Charcoal	Electricity
Wood	**-1.26** (0.09)	0.29 (0.1)	-0.02 (0.05)	0.08 (0.04)	**-3.00** (0.68)	1.88 (0.51)	-0.64 (0.35)	0.37 (0.25)
Kerosene	-0.02 (0.04)	**-0.96** (0.05)	-0.03 (0.02)	0.066 (0.04)	0.02 (0.07)	**-0.69** (0.06)	0.33 (0.07)	0.32 (0.04)
Charcoal	0.17 (0.06)	-0.21 (0.07)	**-0.95** (0.02)	-0.15 (0.06)	0.34 (0.10)	0.04 (0.08)	**-0.33** (0.08)	0.10 (0.07)
Electricity	-0.27 (0.11)	0.27 (0.10)	-0.09 (0.05)	**-0.88** (0.11)	-0.58 (0.27)	0.72 (0.17)	-0.01 (0.19)	**-0.62** (0.21)

Note: The figures in parentheses are the standard deviations. The bold numbers are own-price elasticities.

Kerosene is a substitute for all the other fuel types. Kerosene is mainly used for lighting, so it substitutes electricity for that purpose. It is also used in small cooking stoves, thus substituting firewood and charcoal. Therefore, tampering with the price of kerosene influences the demand for charcoal, firewood and electricity.

5 Conclusion and Recommendations

The study aimed at exploring ways of increasing electricity usage in Uganda and hence improving people's welfare. Electricity is a clean, renewable energy, and its installed capacity exceeds its current demand in the country. In this paper, we analyzed the household demand for energy types using an augmented QUAIDs model that corrects the censored distribution of expenditure shares. The findings show that higher income and living in urban areas increase the electricity demand. We also find that the conditional uncompensated own price elasticities are close to unity. Generally, the results agree with Halvorsen (1975), who found that the long-run own-price elasticity of demand was unity. We extract three main conclusions and policy recommendations from this study:

First, the finding of the Marshallian own price elasticity for electricity close to unity implies that a price reduction will not significantly decrease the revenue of the electricity producers. Thus, a price reduction will provide a win-win, or at least win–not–lose option, for the government, where households' welfare and economic development can be stimulated at a low or no cost.

Second, the estimated income and cross elasticities suggest that Ugandan households do not conform to the energy ladder theory but, rather to energy stacking theory. When incomes increase, households switch from firewood use to charcoal consumption and, after that, use a mix of energy fuels. The cross elasticity between electricity and charcoal is negative, implying the two variables are compliments. This confirms energy stacking theory. On the other hand, results indicate that firewood and charcoal usage increases as household income increases. Therefore, reducing electricity price alone may not alone solve the environmental issues related to firewood and charcoal production and use; other measures are needed to address these problems.

We recommend that the government should address the transmission constraints of electricity by expanding the grid to ensure reliability and expand access. The distributors regulated by ERA should be monitored over prices and costs to keep the electricity prices low.

Abbreviations and Definitions

ERA Electricity Regulatory Authority

OLS Ordinary Least Squares

PPA Power Purchasing Agreement

REP Uganda's Rural Electrification Project

SDGs Sustainable Development Goals

TSO Transmission System Operation

UBOS Uganda Bureau of Statistics

UEB Uganda Electricity Board

UEDCL Uganda Electricity Distribution Company Limited

UEGCL Uganda Electricity Generation Company Limited

UETL Uganda Electricity Transmission Company Limited

Reference List

Abdulai, A. (2002). Household demand for food in Switzerland. A quadratic almost ideal demand system. *Revue Suisse D Economie Et De Statistique*, *138*(1), 1-18.

Banks, J., Blundell, R., & Lewbel, A. (1997). Quadratic Engel curves and consumer demand. *Review of Economics and statistics*, *79*(4), 527-539.

Beenstock, M., Goldin, E., & Nabot, D. (1999). The demand for electricity in Israel. *Energy Economics*, *21*(2), 168-183.

Behera, B., Ali, A., & Marenya, P. (2017). A ladder within a ladder: Understanding the factors **influencing** a household's domestic use of electricity in four African countries. *Energy Economics*, *66*, 167-181.

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

Blimpo, M. P., & Cosgrove-Davies, M. (2019). *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*. World Bank Publications.

Cox, T. L., & Wohlgenant, M. K. (1986). Prices and quality effects in cross-sectional demand analysis. *American journal of agricultural economics*, *68*(4), 908-919.

Deaton, A. (1988). Quality, quantity, and spatial variation of price. *The American economic review*, *78*(3), 418-430.

Deaton, A. (1990). Price elasticities from survey data: extensions and Indonesian results. *Journal of econometrics*, *44*(3), 281-309.

Deaton, A. (1997). *The analysis of household surveys: a microeconometric approach to development policy*. World Bank Publications.

Deaton, A., & Grosh, M. (2000). Consumption in designing household survey questionnaires for developing countries. *Designing Household Survey Questionnaires for Developing Countries: Lessons from Ten Years of LSMS Experience*.

Deaton, A., & Muellbauer, J. (1980). An almost ideal demand system. *The American economic review*, *70*(3), 312-326.

Dewees, P. A. (1989). The woodfuel crisis reconsidered: observations on the dynamics of abundance and scarcity. *World development*, *17*(8), 1159-1172.

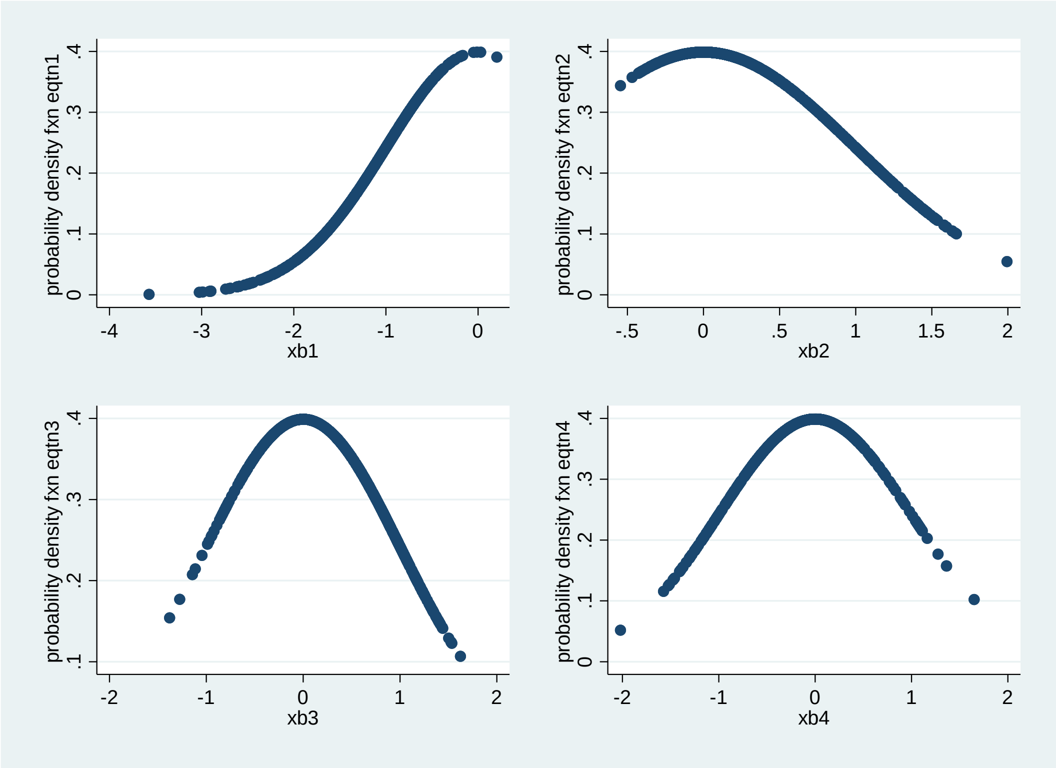
Egeru, A. (2014). *Assessment of forage dynamics under variable climate in Karamoja sub-region of Uganda* [University of Nairobi].

ERA. (2019). *Electricity Supply Industry Performance Report for the Year 2019*.

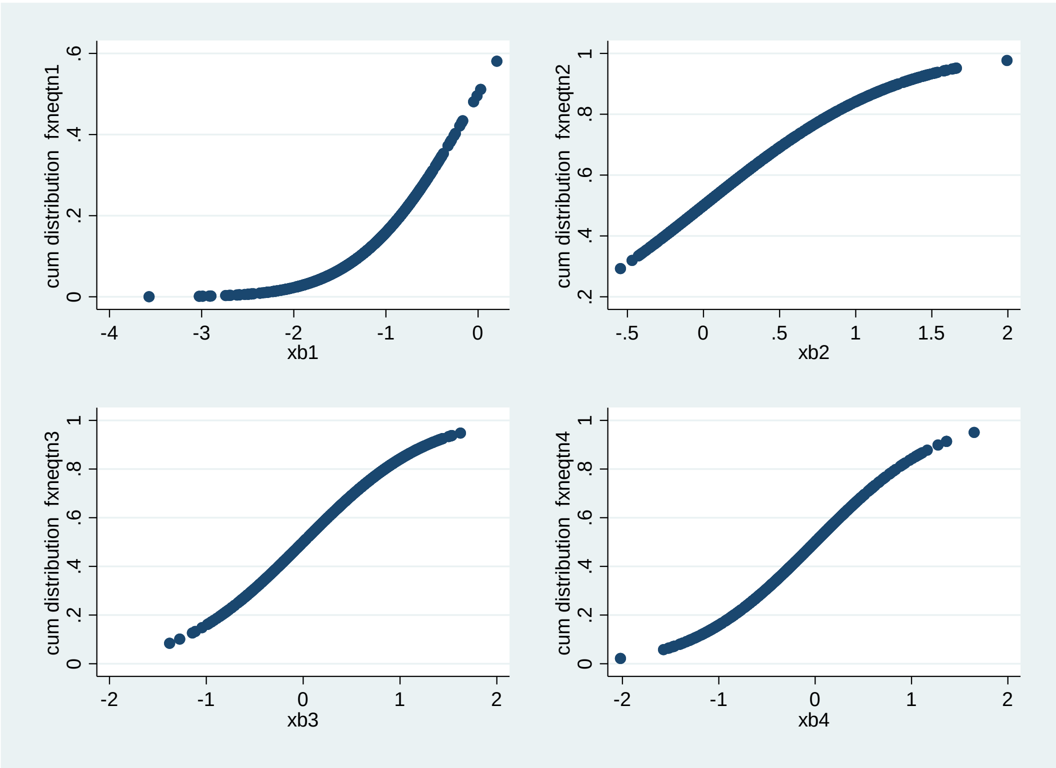
ERA. (2020). *Electricity Supply Industry Performance*.
Gregory, J., & Stern, D. I. (2014). Fuel choices in rural Maharashtra. *Biomass and bioenergy*, *70*, 302-314.
Halvorsen, R. (1975). Residential demand for electric energy. *The review of Economics and Statistics*, 12-18.
Heltberg, R. (2004). Fuel switching: evidence from eight developing countries. *Energy Economics*, *26*(5), 869-887.
Heltberg, R., Arndt, T. C., & Sekhar, N. U. (2000). Fuelwood consumption and forest degradation: a household model for domestic energy substitution in rural India. *Land Economics*, 213-232.
IEA. (2019). *World Energy Outlook*.
IEA. (2021). *World Energy Outlook 2021*. IEA.
Khanal, A. R., Mishra, A. K., & Keithly, W. (2016). Heterogeneity in food demand among rural Indian households: The role of demographics. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, *64*(3), 517-544.
Leach, G. (1992). The energy transition. *Energy Policy*, *20*(2), 116-123.
Masera, O. R., Saatkamp, B. D., & Kammen, D. M. (2000). From linear fuel switching to multiple cooking strategies: a critique and alternative to the energy ladder model. *World development*, *28*(12), 2083-2103.
Me-Nsope, N. M., & Staatz, J. M. (2016). *Household-Level Evidence of Cereals Demand and the Welfare Implications of Cereals Price Shocks in Rural and Urban Mali*.
Nepal, M., Nepal, A., & Grimsrud, K. (2011). Unbelievable but improved cookstoves are not helpful in reducing firewood demand in Nepal. *Environment and Development Economics*, *16*(1), 1-23.
Ngui, D., Mutua, J., Osiolo, H., & Aligula, E. (2011). Household energy demand in Kenya: An application of the linear approximate almost ideal demand system (LA-AIDS). *Energy Policy*, *39*(11), 7084-7094.
Ojelel, S. (2015). *Fuel value indices of fuelwood species and accuracy of K-nearest neighbour technique in woody biomass estimation in Masindi and Nebbi Districts, Uganda* [Makerere University].
Okyay, U., Aricioglu, E., & Yucel, F. (2014). Energy consumption and economic growth nexus: Evidence from developed countries in Europe. *International Journal of Energy Economics and Policy*, *4*(3), 411-419.
Pandey, V. L., & Chaubal, A. (2011). Comprehending household cooking energy choice in rural India. *Biomass and bioenergy*, *35*(11), 4724-4731.
Park, J. L., Holcomb, R. B., Raper, K. C., & Capps Jr, O. (1996). A demand systems analysis of food commodities by US households segmented by income. *American journal of agricultural economics*, *78*(2), 290-300.
Poi, B. P. (2012). Easy demand-system estimation with quaids. *The Stata Journal*, *12*(3), 433-446.
Ray, R. (1983). Measuring the costs of children: an alternative approach. *Journal of Public Economics*, *22*(1), 89-102.
Ray, R. J. J. o. P. E. (1983). Measuring the costs of children: an alternative approach. *22*(1), 89-102.
Ruiz-Mercado, I., & Masera, O. (2015). Patterns of stove use in the context of fuel–device stacking: rationale and implications. *EcoHealth*, *12*, 42-56.
Tabuti, J., Dhillion, S., & Lye, K. (2003). Firewood use in Bulamogi County, Uganda: species selection, harvesting and consumption patterns. *Biomass and bioenergy*, *25*(6), 581-596.
Uganda Bureau of Statistics. (2020). *Statistical Abstract*.
Yen, S. T., Kan, K., & Su, S.-J. (2002). Household demand for fats and oils: two-step estimation of a censored demand system. *Applied Economics*, *34*(14), 1799-1806.

Appendix

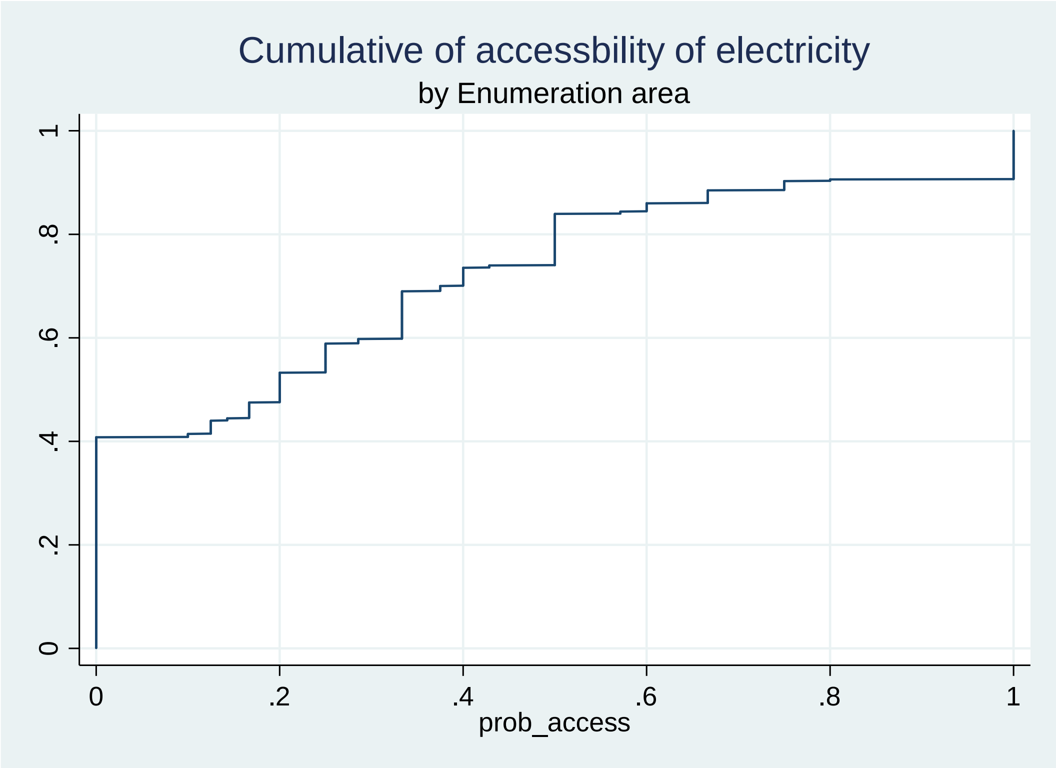
Appendix 1: Probability density functions for wood, Kerosene, Charcoal and Electricity, respectively



Appendix 2: Cumulative distribution functions for wood, Kerosene, Charcoal and Electricity, respectively



Appendix 3: Cumulative distribution functions for wood, Kerosene, Charcoal and Electricity, respectively



Appendix 5: First stage regression

Estimated correlation (rho)matrix and Estimated standard errors

	Firewood	Charcoal	Kerosene	Electricity
firewood	1	.1746	-.2793	-.093
		(.0864)	(.0774)	(.0853)
charcoal	.1746	1	-.3938	-.4958
	(.0864)		(.0641)	(.0541)
kerosen	-.2793	-.3938	1	.3517
	(.0774)	(.0641)		(.0641)
Electricity	-.093	-.4958	.3517	1
	(.0853)	(.0541)	(.0641)	

Averaged Beta-Hat point Estimate and Estimated standard errors

	Firewood	Charcoal	Kerosene	Electricity
lnagehhd	3.377	.2757	.4542	.3251
	(1.3039)	(.7806)	(.8239)	(.7664)
lnhhsize	-.2522	.1667	.5945	-.2345
	(.2783)	(.2124)	(.2216)	(.206)
urban	-.104	-.9502	.9631	.7226
	(.1463)	(.1389)	(.12)	(.1325)
age_hhd	-.0584	.0069	-.0198	-.0151
	(.0265)	(.0175)	(.018)	(.0172)
hhsize	.0697	-.0294	-.1014	.0581
	(.0521)	(.0434)	(.0448)	(.0426)
gender	-.3118	-.083	-.42	.028
	(.1623)	(.1328)	(.1551)	(.1289)
educ_level	-.005	-.0264	.0245	.0474
	(.0131)	(.0102)	(.0107)	(.0103)
married	.6212	.0413	.1603	.0612
	(.1862)	(.1436)	(.1581)	(.1366)
room_no	.0882	-.0961	-.1801	.2634
	(.0588)	(.0524)	(.0512)	(.0541)
_cons	-11.5294	.1041	-1.016	-2.2693
	(3.6922)	(2.1225)	(2.2553)	(2.0769)

Paper 2

Powering Ugandan households: What determines Solar Photovoltaics adoption?

Grace Alinaitwe [a,b]

[a] School of Economics and Business, Norwegian University of Life Sciences, 1432 Ås, Norway;

[b] Department of Management Science, Makerere University Business School, Kampala, Uganda

Abstract

This article examines the factors that determine the adoption and use of solar photovoltaic technologies (PV) in Uganda, using detailed household data from the Uganda 2018/2019 Living Standards Measurement Survey (LSMS). The data was analyzed using a probit model and a multivariate Probit model. We find that the main drivers of the use of solar PVs are savings, income, education of the household head, age of the household head and household size. However, households in urban areas, households with access to grid electricity, households with reliable grid electricity supply, and female-headed households are less likely to adopt solar photovoltaics. The study recommends that the government promote awareness of solar energy and establish credit schemes for solar provision to reduce the burden of initial investment in solar.

Keywords

Multivariate Probit, Renewable energy, Lighting, Solar energy, Uganda

1. Introduction

Electricity is crucial to the welfare of households and is essential in the development process. Electricity provides lighting and power for electronic appliances, power tools, machines, and more. Cooking with electricity reduces indoor pollution, which is a health hazard. Moving to electricity generated from renewables is an important component of policies to reduce global warming. For these reasons, the Sustainable Development Goals (SDGs) focus on ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030. Although Uganda has implemented several programs, e.g., Uganda's Rural Electrification Project (REP), to increase electricity generating capacity and expand the electricity grid to rural areas, most of its population is not connected to the electricity grid. Only 15% of the households accessed electricity through the grid (national or mini grid) in 2019, most of whom lived in urban areas (Uganda Bureau of Statistics, 2019). Many households in Uganda find electricity too costly, both in terms of connection fees and the price of electricity (Blimpo & Cosgrove-Davies, 2019). In 2022, the electricity tariff facing households consisted of monthly service charges of UGX 3360 (USD 0.95), and an electricity charge of UGX 250/kWh (USD 0.07/kWh) for the first 15 kWh consumed in a month and UGX 747.5/kWh (USD 0.21/kWh) after that (Electricity Regulatory Authority [ERA], 2021.

There are also critical constraints related to the electricity transmission grid. Due to a poorly developed grid, many households, firms, and public agencies that would otherwise use electricity cannot access supply through the grid. Furthermore, the extension and maintenance of the grid is costly. Areas without grid access are usually characterized by widely dispersed households in remote communities, making grid electricity availability to most of these areas expensive.

Off-grid solar energy has become a viable alternative (or supplement) to utility-supplied electricity systems in villages and towns across Uganda. Off-grid solar power is expanding rapidly, and the Living Standards Measurement Survey (LSMS) 2018/2019 reported that 36% of the households surveyed used solar energy for lighting. Even households with access to the grid may find it desirable to install solar photovoltaic solar energy as a supplement to grid electricity because the supply from the grid is unreliable and characterized by frequent blackouts both planned and unplanned. Some households have diesel generators as a backup in case of power failure, but for most households, solar photovoltaic units may be a cheaper alternative. Fortunately, Uganda is well endowed with abundant sunshine throughout the year. Therefore, unlike grid electricity, electricity blackouts with solar electricity are less likely.

There are small variations in radiation throughout the year, so there is less need for long-term electricity storage than in places with larger seasonal variations.

Electricity from the grid requires households to purchase grid connections and pay monthly service and energy use charges. In contrast, for solar energy use, the costs usually relate to purchasing the solar kit (equipment), with no recurring (variable) costs. Electricity connection also requires a modern roof (not grass-thatched) to safely install the required standard 230 Volt electricity. However, many houses in Uganda do not comply with this standard (Blimpo & Cosgrove-Davies, 2019). Fortunately, most small solar systems run on 12 Volts and therefore have fewer requirements for house quality and do not require a modern roof for installation.

However, a key question regarding access to electricity is: What are the main drivers of the adoption and use of solar PV in Uganda? Therefore, this study aims to assess and empirically examine the factors that determine the adoption and use of solar photovoltaic technologies in Uganda. The use of solar photovoltaics is highly correlated with other means of lighting, which include electricity and kerosene. The multivariate probit (MVP) model is the best if the variables are highly correlated and there are possible substitutes. Therefore, in our analysis, we employ the MVP model.

We aim to explore ways to increase electrification among Ugandans by encouraging the adoption of decentralized solar energy to supplement the grid and as an alternative in sparsely populated areas where establishing a grid would be very costly. This article contributes to the debate on energy poverty in Uganda by identifying the determinants of the adoption of solar energy, thus contributing to the information pertinent to policy makers about achieving the goal of clean and sustainable energy for all in Uganda by 2030 according to the SDGs.

This study brings forth new evidence on household energy demand in Uganda using the detailed Uganda 2018/2019 Living Standards Measurement Survey (LSMS).

Aarakit et al. (2021a) studied the adoption of solar photovoltaic systems in households in Uganda, using a different data set and methodology. Specifically, they used the 2018 National Electrification Survey data set, and Conditional Mixed Process (CMP) model. This article uses the multivariate probit models, which is the most appropriate model for analyzing solar PV adoption, since solar PV adoption is correlated with the use of grid electricity, kerosene, and other lighting alternatives. Moreover, the study by Aarakit et al. (2021a) does not consider other lighting energy fuels in their model. Solar adoption is highly correlated with other energy lighting fuels and hence needs to be jointly estimated in a multivariate model.

The rest of the paper is organized as follows. Section 2 reviews the relevant literature, while Section 3 outlines the probit and multivariate model, the empirical strategy used, and the data used in the analysis. The results are presented and discussed in Section 4, and concluding remarks are given in Section 5.

2. Literature Review

More than 1.3 billion people worldwide lack access to electricity (Blimpo & Cosgrove-Davies, 2019; Hassan & Lucchino, 2016). According to the National Electrification Survey by UBOS in 2018, only 28% of the Ugandan population had access to electricity (Aarakit, Ssennono, & Adaramola, 2021b). Their results suggested that supply-side gaps constituted the largest proportion of the electricity access deficit in Ugandan households. The supply-side gap due to grid constraints can be resolved by using decentralized solar PV systems. The supply of sunshine in Uganda has a high potential for solar energy production. About 200,000 km^2 of Uganda's land area has solar radiation exceeding 2,000 kWh/m^2 /year (Avellino et al., 2018). Off-grid solar solutions are playing an increasing role in extending energy access to millions of people, especially in sub-Saharan Africa and South Asia. The off-grid solar sector has grown rapidly in the past decade (Rysankova, Peters, & Sturm, 2020). The Uganda Bureau of Statistics (UBOS, 2018) found that although the willingness to pay for electricity services was high among households without access to the grid, many respondents with access to the grid pointed out that the unreliability of the electricity supply was a major challenge.

There are several drivers for the increase in adoption of solar PV systems, including availability, affordability, financial incentives, and awareness through aggressive marketing strategies (Ondraczek, 2013; Tarujyoti, 2012; Urmee & Harries, 2011; Wijayatunga & Attalage, 2005; Aarakit et al., 2021a). (Ondraczek, 2013) found that awareness, availability, and affordability are significant drivers of the rapid adoption of off-grid solar technologies in emerging markets. (Ondraczek, 2013) explains that solar is affordable relative to other fuels due to increasing tariffs and the scarcity of conventional hydro and thermal energy generation in Kenya and Tanzania. Furthermore, in most developing countries, households and businesses with access to electricity still face the challenge of unreliable electricity supply.

Aarakit, Ssennono and Adaramola (2021b) found that the drop in global prices for solar PV systems, inadequate electricity infrastructure (transmission and distribution), commitment and awareness campaigns from government and development institutions, innovations from the solar industry and increased power outages were significant driving forces for the adoption of solar PV systems. In addition, there are tax subsidies for some solar PV systems and components, making solar PV more affordable, thus increasing the adoption rate of solar PV.

However, there are challenges associated with the adoption of solar photovoltaic systems. According to Avellino et al. (2018), in Uganda, energy rules and regulations cut across the energy power generation industries and are not adequately implemented. Similarly, Urmee and Harries (2011) contend that the lack of a national renewable energy policy supporting renewable rural electrification has restricted Bangladesh's successful adoption of solar PVs. Most solar energy consumers depend on small-scale photovoltaic plants for domestic use. However, the construction of the Soroti 10 MW solar power station in 2016, the Tororo 10 MW solar power station in 2017, the Kabulasoke 20 MW solar power station in 2019, and the Mayuge 10 MW solar power station in 2019 is expected to increase the use of solar energy on an industrial scale.

In addition to the challenges mentioned above, poor quality and counterfeit solar products in the market, high cost of quality-verified solar products, lack of after sales maintenance services, limited access to credit finance to acquire quality-verified solar products, and lack of adequate knowledge and operational skills (low awareness of solar PV systems) are hindering successful adoption of solar PV (Mondal & Klein, 2011; Urmee & Harries, 2011; Wassie & Adaramola, 2021).

Several researchers found that households experienced an improved quality of life, a social status, and a better quality of light after adopting solar PVs (Mondal & Klein, 2011; Tarujyoti, 2012; Urmee & Harries, 2011). Furthermore, there was a reduction in lighting expenditure after solar adoption (Obeng & Evers, 2010; Tarujyoti, 2012; Wassie & Adaramola, 2021). For example, Obeng and Evers (2010) found that solar photovoltaic lighting instead of kerosene in rural Ghana reduces energy costs by 1-5 USD per month. Similarly, Wassie and Adaramola (2021) estimated savings of 65-75 USD per year for rural households in Ethiopia if they used solar photovoltaics instead of kerosene. Solar electrification could save 43.68 liters of kerosene consumption and emissions of 107 kg of CO2 per household per year in rural Ethiopia (Wassie & Adaramola, 2021). Using solar photovoltaics instead of kerosene lamps reduces indoor air pollution and health damage (Mondal & Klein, 2011; Tarujyoti, 2012; Wijayatunga & Attalage, 2005).

Solar lighting is a practical and relevant educational input since children can study for extended hours. Moreover, the electrification of health centers and schools provides safer child delivery and improved quality of education(Wassie & Adaramola, 2021). Tarujyoti (2012) also noted that the crime rate was reduced after solar street lighting in Indian rural villages.

On conditional that grid electricity has failed to close the energy poverty gap and solar energy's socioeconomic and environmental benefits, it is worth exploring the determinants of solar PV adoption in the Ugandan context. There is extensive research on the role of solar photovoltaic systems in meeting basic electricity needs and improving the health, education and welfare of rural households and the reasons for their adoption. However, the examination of the determinants of solar PV adoption in Uganda is inadequate.

3. Research Methods

3.1 Model Specification and Econometric Strategy

The econometric analysis was carried out using binary probit regression to analyze the main factors influencing the adoption and purchase of solar PVs in Uganda. Binary probit regression models examine the relationship between a binary dependent variable y and one or more explanatory variables $\boldsymbol{X}$. The dependent variable in this study represents the household's decision to purchase and use solar PV, while the explanatory variables can be discrete or continuous variables. In a sample with n observations the dependent variable is defined as:

$$y_i = \begin{cases} 1 & \text{if respondent } i \text{ adopted solar PV} \\ 0 & \text{otherwise} \end{cases}$$

where $i = 1, \dots, n$.

The decision to adopt or not is related to the explanatory variables through a latent variable, denoted y_i^*, which is specified as:

$$y_i^* = \boldsymbol{\beta X_i} + \varepsilon_i \qquad (1)$$

where $\boldsymbol{\beta}$ is a vector of parameters to be estimated, and ε has a standard normal distribution. The observed outcome is related to the latent variable as

$$y_i = \begin{cases} 1 & \text{if } y_i^* > 0 \\ 0 & \text{if } y_i^* \leq 0 \end{cases} \qquad (2)$$

When using the binary probit model, we use the whole sample but also divide the sample into urban and rural households, as they tend to exhibit different characteristics in terms of fuel choice. This is done to test the consistency of our results.

For robustness checks, the study also uses a multivariate probit (MVP) model to examine the main determinants of the adoption of solar photovoltaics. Multivariate probit models are used to estimate probit models with more than one correlated binary dependent variable. This model is an appropriate model for analyzing the adoption of solar PVs, since the adoption of solar PV is correlated with access to grid electricity, the use of kerosene, and other alternative lighting solutions. Therefore, we estimate a multivariate probit model with four binary outcome choice variables: solar PVs, grid electricity, kerosene, and others (none of the three mentioned choice alternatives). The multivariate probit model has also been applied by (Ali et al., 2019; Behera, Jeetendra, & Ali, 2015; Wassie & Adaramola, 2021) to analyze the determinants of the choice of energy fuels for lighting in the household.

The multivariate probit model generalizes the binary probit model, and is based on four latent variables (Mullahy, 2016):

$$y_{ij}^{*} = \boldsymbol{\beta_j X_{ij}} + \varepsilon_{ij} \qquad (3)$$

where $j = 1,2,3,4$ indexes the alternatives, $\boldsymbol{\beta_j}$ is a vector of parameters for alternative $j, \boldsymbol{X_{ij}}$ are the explanatory variables for alternative j for respondent i. The error term ε_{ij} has a multivariate normal distribution. The observed variables are related to the latent variables as

$$y_{ij} = \begin{cases} 1 & \text{if } y_{ij}^{*} > 0 \\ 0 & \text{if } y_{ij}^{*} \leq 0 \end{cases} \qquad (4)$$

Both binary and multivariate probit models are estimated using maximum likelihood techniques.

3.2 Data

We use the Living Standards Measurement Survey (LSMS) household data for 2018/2019[1] for Uganda. The Uganda Bureau of Statistics UBOS collected the data on behalf of the World Bank. The sampled households were stratified into four regions (Central, Northern, Western and Eastern), districts and enumeration areas. The data consists of 3242 randomly selected households throughout the country. After data cleaning, we used 2818 observations in the analysis. The households eliminated from the sample were due to a lack of data on the major variables The data collected from the household survey included demographic and socioeconomic characteristics and energy sources. It has information on households' lighting choices: grid-electrified, solar-electrified, kerosene lighting, and other lighting fuels.

[1] The full data set can be found on this web https://microdata.worldbank.org/index.php/catalog/3795

The decision to adopt solar electrification depends on many factors, both economic and non-economic. Therefore, the determinants of solar PV adoption may include the following:

1) **Annual household income:** This is measured as total household income over one year. A positive coefficient is expected since income increases purchasing power, thus leading to higher demand for solar PV systems. Guta (2018) argues that solar energy production is a luxury good, especially in low-income countries. Therefore, its adoption is likely to increase with income. Moreover, Smith and Urpelainen (2014) found a positive effect of income on solar adoption in East African countries.
2) **Savings:** This dummy variable takes 1 for having money saved in the bank and 0 for no savings. A positive coefficient is expected since saving increases the ability to cover the up-front investment for solar PV systems.
3) **Education:** This refers to the educational level of the household head (the main breadwinner in the family). It is measured as the number of years of completed schooling. A positive coefficient is expected because, with higher education, there is greater awareness of the uses and benefits of solar PV systems. Guta (2018) argues that education improves employment opportunities. This increases household income, thus the affordability of solar PVS.
4) **Gender of the household head:** It is a dummy variable that takes on 1 for females and 0 otherwise. Here a positive coefficient is expected. This is because, in most developing countries, females are responsible for the laborious energy acquisition (Guta, 2018). Since women are more affected by the lack of energy, they are more willing to pay for renewable energy technologies such as solar PV than their male counterparts. On the other hand, male-headed households could be wealthier, hence affording grid electricity.
5) **Age of the household head:** The coefficient can be positive or negative. Since young people are more aware of the environmental benefits of renewable energy technologies, they may be willing to pay for solar PVS, thus indicating a negative coefficient of age (Guta, 2018). However, Guta (2018) also argues that older people may be wealthier and more likely to invest in solar technologies. Thus, a positive coefficient is expected.
6) **Urban:** This dummy variable takes on 1 if the household is in urban areas and 0 if the household is in rural areas. A positive coefficient is expected. According to Lewis and Pattanayak (2012), urban areas are positively associated with the adoption of cleaner fuels than rural locations. Therefore, we expect solar PV system adoption to be higher

in urban areas than rural ones. Besides, urban households are likely to be close to the market for solar PVs.

7) **Household size:** This may have a positive or negative effect on solar adoption. If the household size is large, the adoption of solar PV is most likely since the fixed cost can be spread over the household members (Guta, 2018). Therefore, a positive effect is expected. However, Guta (2018) argues that household size increases expenditure on various commodities, leaving few resources for solar adoption. In this case, a negative impact is expected.
8) **Electricity prices:** It is measured as the electricity price per kWh. This may positively affect the adoption of solar PVs, and hence a positive coefficient is expected. Since grid electricity and solar energy are potential substitutes, an increase in grid electricity prices may indicate a higher probability of adopting solar PVs. Moreover, Ondraczek (2013), in their study in Kenya and Tanzania, recognizes that escalating hydroelectricity tariffs make solar energy more affordable, thereby driving the uptake of solar PVs.
9) **Reliability of grid-electricity supply:** Here the study uses average electricity hours per day as a proxy for the reliability of grid electricity supply. A negative coefficient is expected. When the grid electricity supply is regular (more extended hours of grid electricity supply), the likelihood of adopting solar PVs diminishes. However, in the case of irregular grid electricity supply, solar PVs are viewed as an alternative option, thereby increasing the probability of adopting solar PVs (Ondraczek, 2013; Aarakit, Ssennono, & Adaramola, 2021b).
10) **Grid connection:** This dummy variable takes on 1 if the household is connected to the grid and 0 otherwise. A negative coefficient is expected since households already connected to the grid may perceive solar adoption as an additional expenditure. They may also perceive solar PVs as having a low-level use (Guta, 2018). Thus, there may be a lock-in effect.

4. Results and Discussion

4.1 Descriptive Statistics

Table 1 reports the summary statistics of all variables used in this study. Only 37% of households used solar PVs, while 37% of the respondents had access to grid electricity. Most Ugandans live in rural areas, so 25% of the surveyed households are in urban areas. The average price of electricity per unit was 689 Ugandan shillings. The average age of the household was 48 years. The average household size was 6 members.

Regarding gender, only 33% were female-headed households. The average electricity hours available was 3 hours per day. This implies electricity is unreliable and is characterized by blackouts in Uganda. On average, 85% of the respondents saved money. The respondents had on average approximately 6 years of completed schooling. The average annual income of the surveyed households was UGX 11,000,000, about USD 2,953 at an exchange rate of UGX 3,725 per 1 USD.

Table 1: Summary Statistics using 2 818 observations.

Variable	units	Mean	Std. Dev.	Min	Max
Solar use (1=solar use)	Dummy	0.37	0.48	0	1
Grid (1= grid access)	Dummy	0.37	0.48	0	1
Urban (1=urban)	Dummy	0.25	0.43	0	1
Electricity price	UGX	689.47	78.81	572.4	771.1
Age hhhead	Years	47.79	15.70	18	98
Household size	Count	5.77	3	1	22
Gender (1=female)	Dummy	0.33	0.47	0	1
Electricity hrs	Hours	2.83	7.39	0	24
Saving	Dummy	0.85	0.36	0	1
Income (106)	UGX	11	353	-430.	18700
Education level	years	5.957	4.46	0	16

Note: *Grid is a dummy variable taking on 1 for access to grid-electricity and 0 for no access, electricity_price is average electricity prices per KWH, age_hhhead is the age of the household head, Household size is the size of the household, electricity_hrs is average electricity hours per day, and education_level is the years of completed schooling of the household head, Urban is a dummy variable taking on 1 for urban location and 0 for rural location, gender is a dummy variable taking on 1 for female and 0 for male and Saving is a dummy variable taking on 1 for if household saved and 0 if household.*

We analyze the correlation matrix between variables, as presented in Table 2. The correlation coefficients measure whether and how strongly solar PV adoption relates to the explanatory variables. As expected, the correlation coefficient (-0.17) between solar use and access to grid electricity is negative, suggesting that the two energy sources are substitutes. Also, urban location, electricity prices, being a female-headed household, and electricity hours are negatively associated with the adoption of solar PVs. Income, age, household size, savings, and education are positively correlated with the adoption of solar PVs.

Table 2: Correlation matrix.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) solar_use	1.000										
(2) grid	-0.170	1.000									
(3) urban	-0.181	0.486	1.000								
(4) Income	0.028	-0.010	0.037	1.000							
(5) electricity_pric	-0.036	0.151	0.099	0.008	1.000						
(6) age_hhd	0.014	-0.026	-0.029	-0.006	0.030	1.000					
(7) household size	0.151	-0.079	-0.073	0.026	0.064	0.050	1.000				
(8) gender	-0.119	0.037	0.008	0.024	0.014	0.152	-0.158	1.000			
(9) electricity_hrs	-0.256	0.498	0.478	-0.003	0.187	-0.044	-0.052	0.015	1.000		
(10) saving	0.097	0.049	0.052	0.011	-0.039	-0.107	0.042	-0.056	0.043	1.000	
(11) education_level	0.054	0.237	0.248	0.043	0.092	0.247	0.036	0.274	0.289	0.133	1.000

4.2 Determinants of solar PV adoption in Uganda

Next, we examine the determinants of solar PVs adoption by applying two econometric analysis models, binary probit, and multivariate probit. Table 3 reports the results on the determinants of solar adoption in Uganda from the binary probit model. The study uses the estimated average marginal effects in the analysis for a better interpretation. Model 1 includes all the variables, model 2 excludes variable urban, while model 3 excludes variable grid. Grid and urban are highly correlated and we include them in different models to reduce the problem of multicollinearity.

As evidenced in model 1 in Table 3, urban negatively affects solar adoption in Uganda. Being in an urban area reduces the probability of adopting solar PVs by 29%, and the variable is statistically significant at a 1% significance level. The marginal effect becomes larger in Model 3 after dropping access to the grid variable. Omitting access to the grid is done to avoid multicollinearity because grid access and urban areas are highly correlated. The negative marginal effect of the variable urban implies that households in urban areas are less likely to adopt solar PVs than their rural counterparts. The argument may be that urban households in Uganda are already connected to grid electricity, hence perceiving solar adoption as an additional expenditure. They may also perceive solar PV as having a low-level use and grid electricity as a better-quality energy source with better voltage. Our results contradict (Lewis & Pattanayak, 2012), who claim that urban areas are positively associated with the adoption of cleaner fuels like solar than their counterparts in rural locations.

Even if (Giri & Goswami, 2017; Wassie & Adaramola, 2021; Aarakit et al., 2021a) found that access to grid electricity significantly and negatively influenced solar PVs adoption, this variable is insignificant in model 1, though rightly signed. Estimating a model that includes both access to grid electricity and the location of the household may (the variables are highly correlated) suffer from multicollinearity problems. Multicollinearity leads to large standard errors, thus making the access to the grid electricity variable insignificant in the model. If we omit the variable "urban", access to the grid electricity variable becomes statistically significant at a 1% significance level, as seen in Model 2. Access to grid electricity reduces the probability of adopting solar PVs by 18%. This may imply that those already connected to the grid may be reluctant to adopt solar PVs because they may perceive solar adoption as an additional cost, and there may be a lock-in effect to grid electricity.

Being a female-headed household reduces the probability of adopting solar PVs by 18%, and the variable is statistically significant at a 1% significance level. This implies a higher likelihood of a male-headed household adopting solar PVs than female-headed ones. Guta (2018) found that male-headed households are less likely to adopt solar PVs than their female-headed counterparts. This finding is against our earlier argument in subsection 3.2 that since women in Africa are more responsible for energy collection, they are more affected by lack of energy and hence may be more willing to pay for cleaner and more convenient energy technologies like solar PVs. Males in Uganda tend to be wealthier than women and may afford the cost of solar PVs. (Wassie & Adaramola, 2021) found the gender of household heads to be insignificant in their study in rural Ethiopia.

Considering electricity hours, a proxy for the reliability of grid-electricity supply, a unit increase in grid-electricity hours reduces solar PVs adoption by 7%, and it is statistically significant at a 1% significance level. This implies that when the grid electricity supply is reliable, the probability of adopting solar PVs falls. This may also indicate that once grid electricity is reliable, it is preferred to solar energy. Also, (Aarakit, Ssennono, & Adaramola, 2021b) point out that increased grid electricity outage significantly drives solar PVs uptake.

We find that an increase in income increases the probability of solar PV adoption. The variable is positive and statistically significant at a 1% significance level. Similar results are reported by (Guta, 2018; Urpelainen, 2014; Wassie & Adaramola, 2021), who found that wealthier households have a higher probability of investing in solar PVs than poor ones. However, the marginal effect of income on solar adoption is negligible. We argue that households with higher incomes are mainly located in urban areas and already have access to grid electricity. Hence, they may perceive solar adoption as an additional cost, and there may be a lock-in effect, thereby having a minimal income effect on solar adoption. Also, (Giri & Goswami, 2017) found that with an increase in income, households are less likely to use solar energy relative to electricity because electricity is a better quality energy source.

In terms of savings, households that save have a 37% probability of adopting solar PVs than those that do not. This may be because, with savings, households can afford to cover the up-front investment of solar PVs.

Concerning household size, the study finds that a unit increase in household size increases the probability of solar adoption by 5%. The variable is positive and statistically significant at a 1% significance level. Likewise, (Giri & Goswami, 2017; Guta, 2018) found that household size positively affects the adoption of solar PVs. This may be because the fixed cost of solar PVs can be spread among household members. On the contrary, (Wassie & Adaramola, 2021) found a negative effect of household size on solar PVs adoption, and they argued that a large house size might mean more rooms to light; hence, they may find solar expensive.

Considering the education of the household head, this variable's marginal effect is positive and statistically significant at a 1% significance level. An increase in the household head's education by one year increases the probability of up taking solar energy by 4%. Similar results are reported by (Giri & Goswami, 2017; Guta, 2018), who argue that education increases purchasing power and awareness, hence the preference for cleaner and more convenient energy sources like solar.

This study found that the age of the household head is a positive determinant of solar PVs adoption, hence similar findings to Guta (2018). It implies that older household heads may be richer and thus can afford to adopt solar PVs. However, age has a minimal effect on solar adoption, as indicated by the small marginal effects in all models. (Wassie & Adaramola, 2021) found that the age of the household head does not influence solar PVs adoption.

Table 3: Determinants of Solar PVs Adoption in Uganda – probit regressions – Full Sample

Variable	(1) dy/dx	(2) dy/dx	(3) dy/dx
Grid	-0.10	-0.18***	
	(0.06)	(0.06)	
Urban	-0.29***		-0.33***
	(0.07)		(0.07)
electricity_price	3.0e-5	1.0e-5	1.0e-5
	(1.0e-4)	(1.0e-4)	(1.0e-4)
age_hhd	1.4e-3**	1.4e-3**	1.4e-3**
	(5.6e-4)	(5.6e-4)	(5.6e-4)
Household size	0.05***	0.05***	0.05***
	(0.01)	(0.01)	(0.01)
Gender	-0.18***	-0.18***	-0.19***
	(0.06)	(0.06)	(0.06)
electricity_hrs	-0.07***	-0.08***	-0.08***
	(0.01)	(0.01)	(0.01)
Savings	0.37***	0.36***	0.37***
	(0.07)	(0.07)	(0.07)
education_level	0.04***	0.04***	0.04***
	(0.01)	(0.01)	(0.01)
Income	2.6e-9***	2.7e-9***	2.7e-9***
	(7.8e-10)	(7.8e-10)	(7.8e-10)
Constant	-1.19***	-1.21***	-1.18***
	(0.25)	(0.25)	(0.25)
Observations	2,818	2,818	2,818

Note: *dy/dx refers to marginal effects from the probit regression. Figures in parentheses are Robust standard errors, ****, **, * stand for statistical significance at 1%, 5%, and 10%levels, respectively.*

Electricity prices do not influence the decision to adopt solar PVs in Uganda since these variables are insignificant, as shown in the models in Table 3.

To examine the sensitivity of the results described in Table 3 we divide the sample into urban and rural households, and the results are reported in Table 4. This is done to check if the results are unaffected by the location of the households. Given that urban and rural households in Uganda exhibit different characteristics, solar adoption factors may differ by location.

Considering the urban households' sub-sample, the significant positive drivers of solar adoption are savings, education of the household head, and household size. The results of the urban sub-sample in Table 4 are similar to those reported in Table 3, except for savings, which now has a much bigger impact on solar adoption with a probability of 58%. The reliability of grid electricity measured by electricity hours has a negative and significant marginal effect (-0.08), which increases slightly compared to the results reported in Table 3—implying that reliable grid-electricity supply reduces the likelihood of adopting solar in urban Uganda. The electricity prices variable is still insignificant, as reported in Table 3. Variables sensitive to sample modification are gender, grid access, age and income, which are now insignificant in the urban sub-sample. The weakening of the results in the urban subsample may be due to differences in the characteristics of rural and urban households.

Table 4: Determinants of Solar PVs Adoption in Uganda – probit regressions, using urban and rural sub-samples.

	(1) Urban sub-sample	(2) Rural sub-sample
Variable	marginal effects	marginal effects
Grid	-0.11	-0.12*
	(0.15)	(0.07)
electricity_price	5.0e-5	4.0e-5
	(1.9e-4)	(1e-4)
age_hhd	0.001	1.5e-3**
	(0.001)	(6.7e-4)
Household size	0.06***	0.04***
	(0.02)	(0.01)
Gender	-0.13	-0.18***
	(0.14)	(0.06)
electricity_hrs	-0.08***	-0.07***
	(0.01)	(0.01)
Savings	0.58***	0.33***
	(0.21)	(0.08)
eduction_level	0.03**	0.04***
	(0.01)	(0.01)
Income	3.8e-11	9.7e-9***
	(1.3e-10)	(1.9e-9)
Constant	-1.79***	-1.20***
	(0.68)	(0.27)
Observations	680	2,138

Note: *Figures in parentheses are Robust standard errors, ****, **, * stand for statistical significance at 1%, 5%, and 10% levels, respectively.*

Considering the rural subsample, the results in Table 4 are very similar to those reported in Table 3 regarding signs and significance. The magnitude of the coefficients changes slightly. Savings, education of the household head, household size, age, and income increase the probability of adopting solar in the rural sub-sample, as reported in Table 4. On the other hand, the results in the rural sub-sample revealed that female-headed households, households with access to the electricity grid, and households with reliable grid-electricity supply are less likely to adopt solar, whereas electricity prices do not statistically significantly affect solar adoption.

4.3 Robustness check using a multivariate Probit Model

Table 5 shows that the correlation coefficients between solar use and the three energy sources are high and negative, as expected. They range from -0.5287 to -0.9985. The negative sign indicates that the energy sources are potential substitutes. The high correlation between the various energy sources and solar use suggests that the Multivariate probit model is the most appropriate for analyzing solar PVs adoption. The model compares factors affecting the adoption of various energy sources, which provides valuable insight. Subsequently, Table 6 reports the estimated multivariate probit coefficients.

Table 5: Correlation Matrix for the various energy sources

Variable	(1)	(2)	(3)	(4)
(1) solar_use	1.000			
(2) grid-electricity	-0.6084***	1.000		
	(0.0374)			
(3) Kerosene_use	-0.5287***	-0.1701***	1.000	
	(0.0283)	(0.0476)		
(4) Others	-0.9985***	-0.994***	-0.9633***	1.000
	(0.0820)	(0.0293)	(0.0315)	

Table 6 reports the results of the multivariate probit model. We observe that the coefficients for urban are negative and significant for solar, kerosene, and others and positive for grid electricity. This implies that urban households are more likely to adopt grid electricity relative to other energy sources. This is because the grid is already in place and hence access to grid electricity; moreover, this kind of electricity is viewed as a better energy source. Access to grid electricity is generally better in urban areas than in rural areas.

Meanwhile, the education level of the household head is positively associated with the adoption of solar and grid electricity and negatively correlated with other energy sources. This suggests that higher levels of education may lead to increased purchasing power and awareness; hence, such households will prefer cleaner and more efficient energy sources. The findings are in line with (Mwalule & Mzuza, 2022) who found that the level of education attained had an influence on the peoples' choices to use solar technology. Furthermore, household size increases the likelihood of using solar energy, and decreases the probability of using other energy sources but does not significantly affect the use of grid electricity and kerosene. As expected, saving increases the probability of adopting solar PVs. We observe that a household that saves is less likely to use other energy sources. This implies that by saving, households find the up-front investment in solar affordable besides being a clean energy source.

Regarding the age of the household head, age increases the probability of adopting solar energy and reduces the likelihood of using other energy sources. This may indicate that older people are wealthier and thus can afford clean energy like solar. However, the age of the household head also increases the probability of using kerosene. The reasoning here is that older people are accustomed to using kerosene hence a lock-in effect, and they may lack awareness of modern energy technologies like solar and grid electricity. Concerning the gender of the household head, being a female-headed household reduces the probability of adopting solar energy but increases the likelihood of using grid electricity. Males can afford it, given that, on average, males are richer than females in Uganda. Focusing on income, though rightly signed (positive coefficient), its marginal effect on all energy sources is very minimal.

Table 6: Determinants of solar PV adoption in Uganda – Multivariate Probit Model.

Variable	(1) Solar	(2) Grid-electricity	(3) Kerosene	(4) Others
Urban	-0.6674***	1.4588***	-0.136**	-0.2341***
	(0.0662)	(0.0699)	(0.0640)	(0.0644)
eduction_level	0.0219***	0.0840***	-0.0044	-0.0599***
	(0.0061)	(0.0084)	(0.0063)	(0.0067)
age_hhd	0.0038**	-0.0012	0.0033**	-0.0064***
	(0.0016)	(0.0022)	(0.0017)	(0.0017)
Household size	0.0492***	-0.0093	-0.0121	-0.0258***
	(0.0083)	(0.0122)	(0.0089)	(0.0089)
Gender	-0.2290***	0.2600***	0.0805	-0.0576
	(0.0560)	(0.0753)	(0.0567)	(0.0551)
Savings	0.3621***	0.082	0.0187	-0.3301***
	(0.0709)	(0.1058)	(0.0717)	(0.0669)
Income	0.0000	0.0000	0.0000	0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Constant	-1.0551***	-2.2700***	-0.7140***	0.6133***
	(0.1205)	(0.1879)	(0.1274)	(0.1241)
Observations	2,818	2,818	2,818	2,818

Note: *Figures in parentheses stand for Robust standard errors, and ****, **, * stand for statistical significance at 1%, 5%, and 10% levels, respectively.*

5. Conclusions

This study empirically examined the factors affecting the adoption of solar PVs in Uganda. The findings from the probit and multivariate probit models are that household savings, education of the household head, age of the household head, household size, and income drive the adoption of solar PVs in Uganda. However, households in urban areas, households with access to grid electricity, households with reliable grid electricity supply, and female-headed households are less likely to adopt solar PVs. Considering a multivariate model, which has various energy sources, households in urban areas prefer grid electricity to solar, kerosene, and other energy sources. Solar PV kits can be costly, while, with grid electricity, there may be less upfront investment, but you pay monthly. For households with liquidity constraints, the difference in the cost profile over time could be decisive.

Given that many households in Uganda live below and around the poverty line, they cannot pay for solar panels as, in most cases, the entire investment is upfront. More research is needed through market innovation of various solar panels to further reduce costs for the end user. The government should establish credit schemes for solar provision to lessen the burden of upfront investment in solar, making it relatively affordable. The government should also educate people, mainly rural households, about the uses and benefits of clean solar energy. Education creates awareness of clean energy, such as solar energy, which increases its adoption.

Abbreviations

The following abbreviations were used in this paper.

ERA Electricity Regulatory Authority

REP Uganda's Rural Electrification Project

SDGs Sustainable Development Goals

UBOS Uganda Bureau of Statistics

MVP model Multivariate Probit model

Reference List

Aarakit, S. M., Ntayi, J. M., Wasswa, F., Adaramola, M. S., & Ssennono, V. F. (2021a). Adoption of solar photovoltaic systems in households: Evidence from Uganda. *Journal of Cleaner Production*, *329*, 129619.

Aarakit, S. M., Ssennono, V. F., & Adaramola, M. S. (2021b). Estimating market potential for solar photovoltaic systems in Uganda. *Frontiers in Energy Research*, *9*, 602468.

Ali, A., Rahut, D. B., Mottaleb, K. A., & Aryal, J. P. (2019). Alternate energy sources for lighting among rural households in the Himalayan region of Pakistan: Access and impact. *Energy & Environment*, *30*(7), 1291-1312.

Avellino, O. W. K., Mwarania, F., Wahab, A.-H. A., Aime, K. T., & Aime, K. (2018). Uganda solar energy utilization: current status and future trends. *International Journal of Scientific and Research Publications (IJSRP)*, *8*(3), 317-327.

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

Blimpo, M. P., & Cosgrove-Davies, M. (2019). *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*. World Bank Publications.

Giri, M., & Goswami, B. (2017). Determinants of households’ choice of energy for lighting in Nepal. *Economics and Business Letters*, *6*(2), 42-47.

Guta, D. D. (2018). Determinants of household adoption of solar energy technology in rural Ethiopia. *Journal of Cleaner Production*, *204*, 193-204.

Hassan, F., & Lucchino, P. (2016). *Powering Education* (CEP Discussion Paper, Issue. L. Center for economic performance.

Lewis, J. J., & Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A systematic review. *Environmental health perspectives*, *120*(5), 637-645.

Mondal, A. H., & Klein, D. (2011). Impacts of solar home systems on social development in rural Bangladesh. *Energy for Sustainable Development*, *15*(1), 17-20.

Mullahy, J. (2016). Estimation of multivariate probit models via bivariate probit. *The Stata Journal*, *16*(1), 37-51.

Mwalule, G., & Mzuza, M. K. (2022). Factors Influencing the Use of Solar Energy Technology in a Local Township of Blantyre City, Malawi. *Open Journal of Energy Efficiency*, *11*(1), 1-9.

Obeng, G. Y., & Evers, H.-D. (2010). Impacts of public solar PV electrification on rural micro-enterprises: The case of Ghana. *Energy for Sustainable Development*, *14*(3), 223-231.

Ondraczek, J. (2013). The sun rises in the east (of Africa): A comparison of the development and status of solar energy markets in Kenya and Tanzania. *Energy Policy*, *56*, 407-417.

Rysankova, D., Peters, K., & Sturm, R. (2020). *Off-Grid Solar Market Trends Report 2020*.

Smith, M. G., & Urpelainen, J. (2014). Early Adopters of Solar Panels in Developing Countries: Evidence from T anzania. *Review of Policy Research*, *31*(1), 17-37.

Tarujyoti, B. (2012). Impact of solar energy in rural development in India. *International journal of environmental science and development*, *3*(4), 334-338.

Uganda Bureau of Statistics. (2019). *STATISTICAL ABSTRACT*.

Urmee, T., & Harries, D. (2011). Determinants of the success and sustainability of Bangladesh’s SHS program. *Renewable Energy*, *36*(11), 2822-2830.

Urpelainen, J. (2014). Grid and off-grid electrification: An integrated model with applications to India. *Energy for Sustainable Development*, *19*, 66-71.

Wassie, Y. T., & Adaramola, M. S. (2021). Socio-economic and environmental impacts of rural electrification with Solar Photovoltaic systems: Evidence from southern Ethiopia. *Energy for Sustainable Development*, *60*, 52-66.

Wijayatunga, P. D., & Attalage, R. A. (2005). Socio-economic impact of solar home systems in rural Sri Lanka: a case-study. *Energy for Sustainable Development*, *9*(2), 5-9.

Paper 3

Article

Assessing the Relationship Between Fuel and Charcoal Prices in Uganda

Grace Alinaitwe [1,2] and Olvar Bergland [1,3]

[1] School of Economics and Business, Norwegian University of Life Sciences, 1432 Ås, Norway
[2] Department of Management Science, Makerere University Business School, Kampala, Uganda
[3] School of Economic Sciences, Washington State University, Pullman, WA 99163, USA
* Correspondence: olvar.bergland@nmbu.no

Abstract: Charcoal is a dominant energy source in urban areas of Uganda, and increases in retail prices in the past have led to social unrest. This paper assesses the relationship between charcoal prices and fuel prices to determine whether fuel prices influence the retail price of charcoal. We specify a transportation cost model for charcoal supply and derive the reduced form equilibrium price function. We estimated an error-correction model for the equilibrium price with monthly data for the period July 2010 through January 2021 to determine whether there are long-term and/or short-term relationships between the retail and supply prices of charcoal and the prices of diesel and other fuel types. As the price data is integrated of order zero and one, the autoregressive distributed lag (ARDL) bounds test is used. The results show that there is a long-term relationship (cointegration) between the retail price of charcoal and the supply prices of diesel and the price of supply and kerosene, which is a substitute energy source for the end users. Firewood and diesel prices are not statistically significant in the model. The long-term equation includes a positive trend, indicating that the retail price of charcoal is increasing more over time than would be implied by the supply price of charcoal and the price of kerosene. Increasing demand from a growing urban population and reduced supply from deforestation are trends that will increase the equilibrium price of charcoal, which we observe.

Keywords: charcoal; fuel; prices; cointegration; long-run equilibrium; Uganda

JEL Classification: O13; Q41; C22

Citation: Alinaitwe, G.; Bergland, O.. 2023. Title. *Economies* 1: 0. https://doi.org/

Received:
Revised:
Accepted:
Published:

1. Introduction

The household decision on the type of cooking fuel to use has important economic and environmental implications. At the household level, cooking fuel use is influenced by both availability of particular appliance types, supporting fuel availability, and the household utility associated with the various options. In addition to the availability considerations, households are likely to choose a cooking option that is considered affordable or whose price is in line with the household budget allocations. In sub-Saharan African nations, the main fuel sources for cooking are firewood and charcoal, with charcoal dominating in urban areas (D'Agostino et al. 2015; Rose et al. 2022). Nzabona et al. (2021) reported that almost 80% of the households in Kampala, Uganda's capital, used charcoal for cooking. Households prefer charcoal for cooking, as it is often a cheaper and more dependable energy source than alternative options such as electricity, liquefied natural gas (LNG), and kerosene (Aarakit et al. 2021; D'Agostino et al. 2015; Doggart et al. 2020).

The "Walk-to-Work" protests in Uganda in 2011 were at least in part due to sharp increases in fuel and food prices (Mutyaba 2022).During this time, charcoal prices increased sharply. A common belief is that the increases in charcoal prices were and are due to the rise in diesel fuel prices. However, there are other factors that could also influence charcoal prices. Which of these factors, if any, and to what extent they impact the retail price are important for understanding the price formation process and for the design of any policy interventions.

The motivation for this paper is the claim that increasing diesel fuel costs are driving increases in retail charcoal prices. Generally, prices of goods traded in markets are affected by both demand and supply side factors, including transportation costs. Therefore, an increase in retail prices for charcoal could be attributed to increased transportation costs, either as a result of increased fuel costs or as a result of increased transportation distance due to deforestation and/or land use conversions. Prices along spatially distributed supply chains are expected to obey a weak law of one price (Fackler and Goodwin 2001; Huffaker et al. 2021) where price differences reflect transportation and transaction costs and market conditions (Acosta et al. 2021).

This article assesses the relationship between charcoal prices and fuel prices to determine whether fuel prices influence the retail price of charcoal. The availability of suitable data for the empirical analysis of price transmission and market integration is a challenge in general (Barrett 1996; von Cramon-Taubadel 2017). Using monthly price data for the period July 2010 to January 2021 for charcoal at different locations along the supply chain, we empirically tested whether there are long-term and/or short-term relationships among charcoal prices and the prices of diesel and other fuel types using an error-correction model.

The role of charcoal as an energy source and as a contributing factor to deforestation is widely researched (Branch et al. 2022; Chidumayo and Gumbo 2013; Masera et al. 2015). Although there are studies investigating the supply and value chains of charcoal (Agbugba and Obi 2013; Agyei et al. 2018; Khundi et al. 2011; Schure et al. 2013; Shively et al. 2010; Worku et al. 2021), these articles, except one, do not explicitly address any of the factors that influence charcoal prices. Agbugba and Obi (2013) use daily prices for a single month to assess price transmission among supply, wholesale, and retail levels in Nigeria. Their analysis is short-term and does not include any external cost factors such as fuel prices. Thus, this paper adds novel empirical insights into price formation and price linkages in the charcoal supply chain.

The paper continues with a review of the literature in the next section (Section 2). Section 3 first describes the charcoal supply chain in Uganda and then presents a theoretical land rent model for the price of charcoal in a central market. The data, data sources, and the autoregressive distributed lag (ARDL) model are described in Section 4. The results are presented and discussed in Section 5, and Section 6 concludes.

2. Literature Review

The published literature on charcoal, or, more broadly, woodfuel, has focused on three areas: i) the environmental impact and sustainability of production (Chidumayo and Gumbo 2013; Mensah et al. 2022), ii) the livelihood and poverty of producers (Brobbey et al. 2019; Khundi et al. 2011), and iii) the usage of charcoal, including poverty and health issues, and household's choice of fuel, or type of energy, especially for cooking (D'Agostino et al. 2015; Doggart et al. 2020; Nzabona et al. 2021; Poblete-Cazenave and Pachauri 2018). Arnold et al. (2006) give a broad overview of the literature on the woodfuel situation in developing countries. Rose et al. (2022) analyzed the current demand for charcoal in sub-Sahara Africa, and their forecasts indicate that strong urban growth will keep charcoal use high for decades. Mensah et al. (2022) review the charcoal production in the same area and raise concerns about how an informal sector based on small-scale production using inefficient technologies can meet the increasing demand for charcoal.

The literature on charcoal production, consumption, and prices is predominantly descriptive and often not based on formal empirical analysis. A recent comprehensive review of the published literature on charcoal in Tanzania by Nyamoga and Solberg (2019) is instructive. They identify 42 studies that deal with the production and consumption of charcoal; however, only six of these studies include any statistical analysis. Of these six studies, only four state an explicit behavioral model for producers or consumers. Three of these studies investigate the determinants of charcoal consumption (D'Agostino et al. 2015;

Hosier and Kipondya 1993; Nyamoga et al. 2022), while Monela et al. (2007) investigate the socioeconomic factors that influence charcoal production decisions. However, none of these studies investigate market integration or price transmission along the supply chain.

Charcoal supply chains have been described and analyzed in several countries, including Uganda (Shively et al. 2010), Nigeria (Agbugba and Obi 2013), Mozambique (Baumert et al. 2016), Ghana (Agyei et al. 2018), and Ethiopia (Worku et al. 2021). Schure et al. (2013) study the supply chains in Central and West Africa. These studies are informative with respect to the organization and functioning of the supply chain, including the distribution of profit along the supply chain.

Agbugba and Obi (2013) collected prices on a daily basis for a single month from charcoal producers, wholesale agents and retailers in the Abia State of Nigeria. Granger causality tests show that there is a positive influence from the producer's price to the wholesale price, but not the other way around. Furthermore, there is a bilateral relationship between wholesale and retail prices.

Worku et al. (2021) using survey data obtained from charcoal producing households in the Amhara region of Ethiopia, estimate a linear regression model with market supply of charcoal as the dependent variable, and household characteristics, distance from the market, and price paid to producers as explanatory variables. They find a positive relationship between the quantity supplied and price, but no relationship between the quantity and the distance to the market. The relationship between price and distance to the market is not analyzed.

In contrast to Worku et al. (2021), Hofstad and Sankhayan (1999) and Sankhayan and Hofstad (2000), informed by economic theory, use regression models with local charcoal prices as the dependent variable and the linear distance from the central market place as the single regressor. They find a clear negative relationship between distance from the market and price of charcoal in both Tanzania and Uganda.

Nyamoga and Solberg (2019) concluded that much of the reviewed literature on charcoal production and consumption lacks clear behavioral models and testable hypotheses. The studies by Hofstad (1997) and Sankhayan and Hofstad (2000) are exceptions, as they are based on an economic model of land rent (Randall and Castle 1985). This lack of theoretical foundation in the charcoal literature is in contrast to the literature on market integration and price transmission along supply chains, which has a strong price theoretic foundation (Fackler and Goodwin 2001; McNew 1996; von Cramon-Taubadel 2017). The study of spatial and temporal price relationships has a long history in agricultural economics (Barrett 1996; Takayama and Judge 1971; von Cramon-Taubadel 2017)[1] and remains an active research area, with recent examples exploring spatial market integration in the EU (Roman and Žáková Kroupová 2022) and price transmission in international markets under trade wars (Barboza Martignone et al. 2022).

3. The Charcoal Sector

3.1. Energy in Uganda

The population of Uganda was about 41 million in 2021. Approximately 90% of the total energy supply in 2021 of 22 million tonnes of oil equivalent was bioenergy, mainly wood and charcoal (IEA 2023). Almost 2% of the energy came from electricity, 80% of which is produced by hydroelectric power plants. Imported oil products, mostly petrol and diesel for transportation, represented nearly 9% of the total energy supply. About 6% of the imported oil products is kerosene for household use. In 2022, electricity access was limited to about 19% of the population having on-grid access and 38% having off-grid access (MEMD 2023). Although the access rate to electricity has increased from 5% in 2002, electricity security in Uganda remains low (Wabukala et al. 2022).

In Uganda, as in most sub-Sahara African countries, the primary energy sources for cooking are charcoal and firewood. Charcoal is the dominant energy source (65.7

[1] Also, see the recent reviews by von Cramon-Taubadel and Goodwin (2021) and Graubner et al. (2021).

%) for cooking in urban areas (MEMD 2016). In Kampala, the dominance of charcoal is even greater at 77.8 % (Nzabona et al. 2021). A recent study finds that energy poverty is widespread in Uganda, although with important geographical and social differences (Ssennono et al. 2021). The cost of charcoal is one of the factors included in their assessment of energy poverty.

3.2. The Charcoal Supply Chain

A charcoal supply chain would typically include these key steps: production, transportation, wholesale, retail, and consumption with different economic entities engaged in the different stages (Baumert et al. 2016; Sander et al. 2013). According to Shively et al. (2010), Uganda's charcoal value chain consists of producers, agents, traders, transporters, retailers, and consumers. Agents act as intermediaries between producers and wholesale traders and earn commissions for connecting producers with traders. Wholesale traders purchase charcoal through agents or directly from producers and sell it to retailers, but do not sell charcoal directly to consumers.

As most of Uganda's charcoal production takes place on private lands, production falls under the jurisdiction of the District Forest Services. Following a major forest sector decentralization reform in 2003, the District Forest Service has been responsible for monitoring and enforcing rules related to charcoal production on private land. The District Forest Service also plays an important role in regulating the transport of charcoal beyond district boundaries. Charcoal production is carried out primarily on a small scale, involving a large number of producers. Shively et al. (2010) noted inadequate capacity in the District Forest Service to monitor and enforce regulations on charcoal production. Instead of using charcoal production licenses as a means to collect revenues, the districts are relying on loading fees or taxes levied at the transportation stage in the value chain.

The main marketplace for charcoal is the city of Kampala (MEMD 2016). Transportation takes place along a few main roads leading into the city. Production is spread out and its specific location depends on the availability of suitable forest species, manpower, and transportation possibilities.

3.3. Price Formation

We can use land rent theory (Alonso 1964; Randall and Castle 1985) in the tradition of von Thünen to conceptualize the formation of prices along the value chain of charcoal from remote producers to the central market place of Kampala. The simplified theoretical model in this research tradition is of a long narrow city with a central business district (or market place). The model can be extended to a spatial equilibrium model (Fujita 1989). Hofstad (1997) uses a spatial and dynamic land use model to analyze the distribution of charcoal production around the city of Dar es Salaam.

Consider a central marketplace where charcoal is sold. Emanating from the marketplace is a road along which charcoal is produced. Charcoal is produced with a common known technology at a unit cost c_p. Charcoal is transported to the central marketplace by trucks. Assume that the transport business is competitive with unit costs tx, where x is the distance from the producer to the market and t are the costs per unit of distance. Let c_m be the wholesale and retail transaction costs associated with the local and central markets. These costs can include loading fees, transport and council taxes, as well as any payments necessary to operate in the central market. In equilibrium, the marginal unit of charcoal will be produced at the location x_m and the marginal producer at this location will be paid c_p, that is, a price equal to the cost of production.

Producers of charcoal closer to the marketplace than the marginal producer will earn a locational rent as the roadside supply price at location $x < x_m$ follows the price gradient, $p(x)$, defined by the difference in transportation cost

$$p(x) = t(x_m - x) + c_p. \quad (1)$$

Let p^c denote the central market price of charcoal in a competitive situation. This price is equal to the marginal cost of providing this unit in the market place, that is:

$$p^c = c_m + tx_m + c_p. \tag{2}$$

Assuming a uniform distribution of charcoal production along the road, the aggregate quantity produced is:

$$q^s = \mu(x_m - x_u) \tag{3}$$

where x_u is the limit of how far away from the market place the urban (or agricultural) area extends, and μ is the supply of charcoal per distance unit. If charcoal production is not evenly distributed along the road, the supply at distance x could be given a supply density function $h(x) \geq 0$, and the aggregate supply would be the integral of the supply density from x_u to x_m.

Let the aggregate demand function for charcoal in the central market place be

$$q^d = d(p^c, z^d) \tag{4}$$

where z^d is one or more exogenous demand shifters.

In market equilibrium $q^s = q^d$. Combining equations (2), (3) and (4) we can solve for the location of the marginal producer (x_m) as a function of external factors. Substituting this location in the market price equation (2) gives the reduced form price equation as:

$$p^c = f(t, z^d, c_p, x_u, \mu) \tag{5}$$

where transaction costs, c_m, are kept constant.

Following the analysis of Randall and Castle (1985), an increase in the demand for charcoal will increase the central market price p^c, increase the distance to the marginal producer, and shift the roadside price gradient in equation (1) outward. The average price along the road will increase as well.

An increase in fuel prices increases transport costs t. This will lead to an increase in the central market price, and the location of the marginal producer will be closer to the market. Additionally, the roadside price gradient becomes steeper and the average roadside price increases. A reduction in available charcoal, say due to deforestation, will shift the marginal producer farther away from the market, resulting in a higher market price, with all other factors constant.

The final price in the central market place is influenced by other factors beyond those included in this transportation cost model. For example, on the demand side, kerosene is a possible substitute for charcoal, as it is used in small fire stoves not only for cooking but also for lighting. Firewood is another possible substitute fuel source. Although firewood is used mainly in rural areas and not in urban areas, it can compete for limited resources in the production of charcoal. If firewood and charcoal are more likely to be actual substitutes in rural areas, there could be linkages between firewood prices and the supply price of charcoal. Olabisi et al. (2019) finds evidence of substitution between charcoal and kerosene in Tanzania.

A detailed empirical analysis of the formation of prices along the charcoal value chain with a credible assessment of the causal effects of population growth and deforestation on the retail price of charcoal would require a structural econometric model estimated using spatial time series data in combination with forest inventory data. However, quantity data are not available, nor population or forest data. Instead, with access to only price data, we will use the reduced form price function in equation (5) and other econometric methods based on cointegration to investigate whether there are any long-term relationships that influence retail charcoal prices (McNew 1996; Rapsomanikis et al. 2006).

4. Data and Methods

4.1. Data Sources

The Uganda Bureau of Statistics (UBOS) collects detailed price statistics on a monthly basis for a number of goods to support the calculation of their consumer price index. Here, we use disaggregated UBOS price data for the period starting in July 2010 and through January 2021, for diesel (p^d), kerosene (p^k), firewood (p^f) and charcoal. The average price of charcoal collected in different markets in Kampala is taken to represent the price of charcoal in the central market, denoted p^c. UBOS also collects charcoal prices in the cities of Arua, Kabarole, Gulu, and Jinja. These markets are in charcoal producing areas or along key transportation routes (Haysome et al. 2021). Thus, these prices are taken to represent the supply price of charcoal, denoted p^s. The definitions of the price variables are summarized in Table 1.

Table 1. Price variables constructed from Uganda Bureau of Statistics consumer price index surveys.

Symbol	Name	Units	Geographical area
p^c	Charcoal	kg	Kampala
p^f	Firewood	kg	Uganda
p^k	Kerosene	liter	Uganda
p^d	Diesel	liter	Uganda
p^s	Supply	kg	Arua, Kabarole, Gulu, Jinja

Accurate and up-to-date population numbers for Uganda are not available. A commonly used source for population data is the World Urbanization Prospects of the United Nations. This source provides estimates and projections for major urban centers around the world, including Kampala. However, these population numbers represent population estimates every five years, and any interpolation of these numbers on an annual scale resulted in smooth annual population growth of approximately 5% over the 2010-2021 period, as can be seen from Figure 1 which shows projections and interpolations from World Population Review[2].

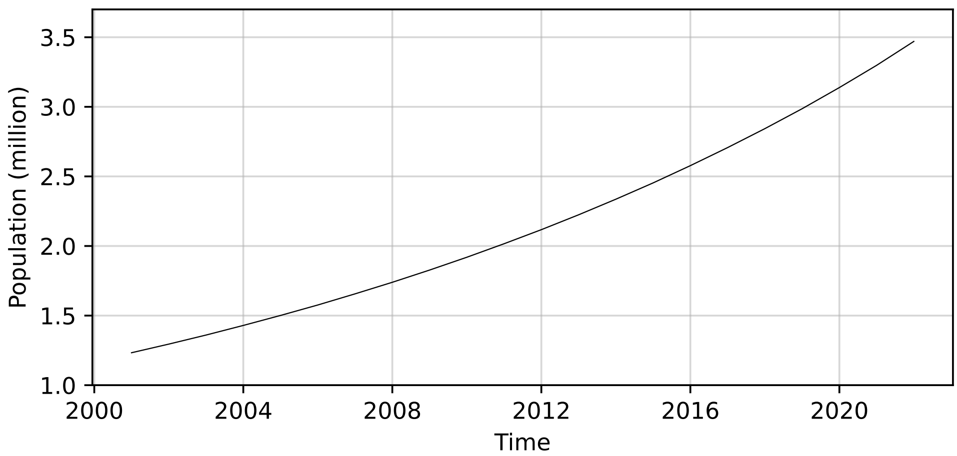


Figure 1. Population in the larger Kampala area (millions). Estimates and projections from World Population Review. Source: World Population Review (https://worldpopulationreview.com/).

The Global Forest Watch project[3] collects data and provides assessments of the extent of tree cover loss in a number of countries. The estimated area covered by forest in Uganda

[2] https://worldpopulationreview.com/
[3] https://www.globalforestwatch.org/

is shown in Figure 2. There is a fairly steady downward trend in forest cover. Increasing demand will, everything else constant, intensify tree harvesting and expand the harvested area (Hofstad 1997). The managed forest will have a changing tree cover throughout the rotation period and will be recorded as lacking tree cover for a period after harvest. Forest cover could act as a proxy for the availability of raw material for charcoal production.

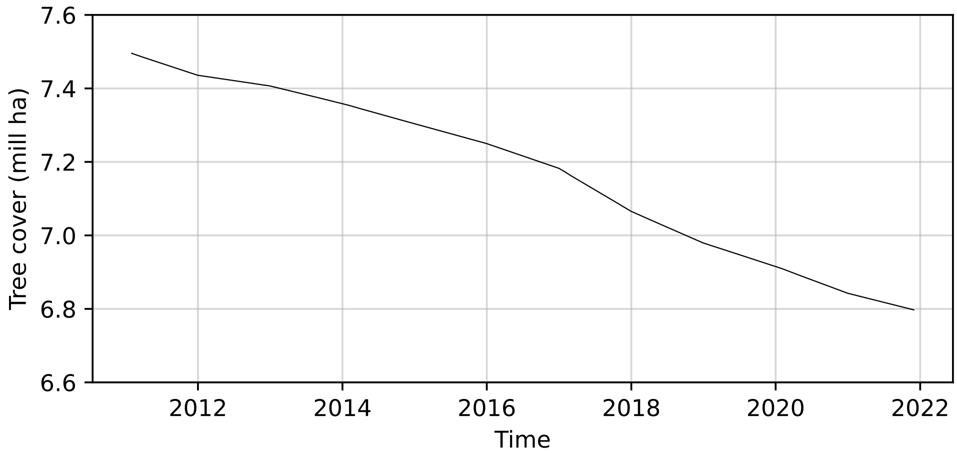


Figure 2. Total land area covered by forest in Uganda in million hectares. Estimates from Global Forest Watch. Source: Global Forest Watch (https://www.globalforestwatch.org/).

However, as both population size and forest cover are estimates and projections available at a coarser time scale than the price data, both series would need to be interpolated to match the time scale of the price data. The interpolated series would have long periods with constant change, thus containing little information and possibly causing multicollinearity problems if the series are differentiated. Instead of using estimated population and forest cover variables, these variables are replaced with a trend variable in the empirical analysis. This trend variable represents, on the one hand, the increase in demand as a result of population growth in the Kampala market; and, on the other hand, it represents the effect, if any, of reduced supply due to deforestation and increased transportation distance.

4.2. Summary Statistics

The time paths for the nominal prices are shown in Figure 3. Charcoal prices (top panel) increased sharply in July–September 2011. The other price series show a similar pattern, although with a more gradual increase over a longer period. Both diesel and kerosene experienced price increases in the period 2016–2018. Nominal charcoal prices were fairly stable from late 2011 until late 2017, and then increased until 2020.

Adjusting for inflation in the period using the UBOS consumer price index (CPI), we see from Figure 4 that both diesel and kerosene prices decreased in real terms from 2011 to 2017. The increase in real charcoal prices from late 2017 overlaps in time with an increase in real diesel prices. Real prices for firewood and supply charcoal do not show a discernible trend, but with a jump in late 2011.

Table 2 presents the summary statistics for the real prices measured in real 2021 Ugandan Shilling (UGX). The correlation matrix for real prices is shown in Table 3. The market price of charcoal in Kampala has a positive correlation with the supply price of charcoal (0.638). This positive correlation between essentially the same product is to be expected in two different places along the supply chain. There is also a clear negative correlation between the market price of charcoal and the price of diesel (-0.513), which is somewhat surprising given the initial concern that increasing charcoal prices may have been driven by higher fuel costs in the transportation sector. There is a very high positive correlation between diesel and kerosene (0.957). These two products are based on crude oil and are both imported, and the high correlation coefficient reflects this.

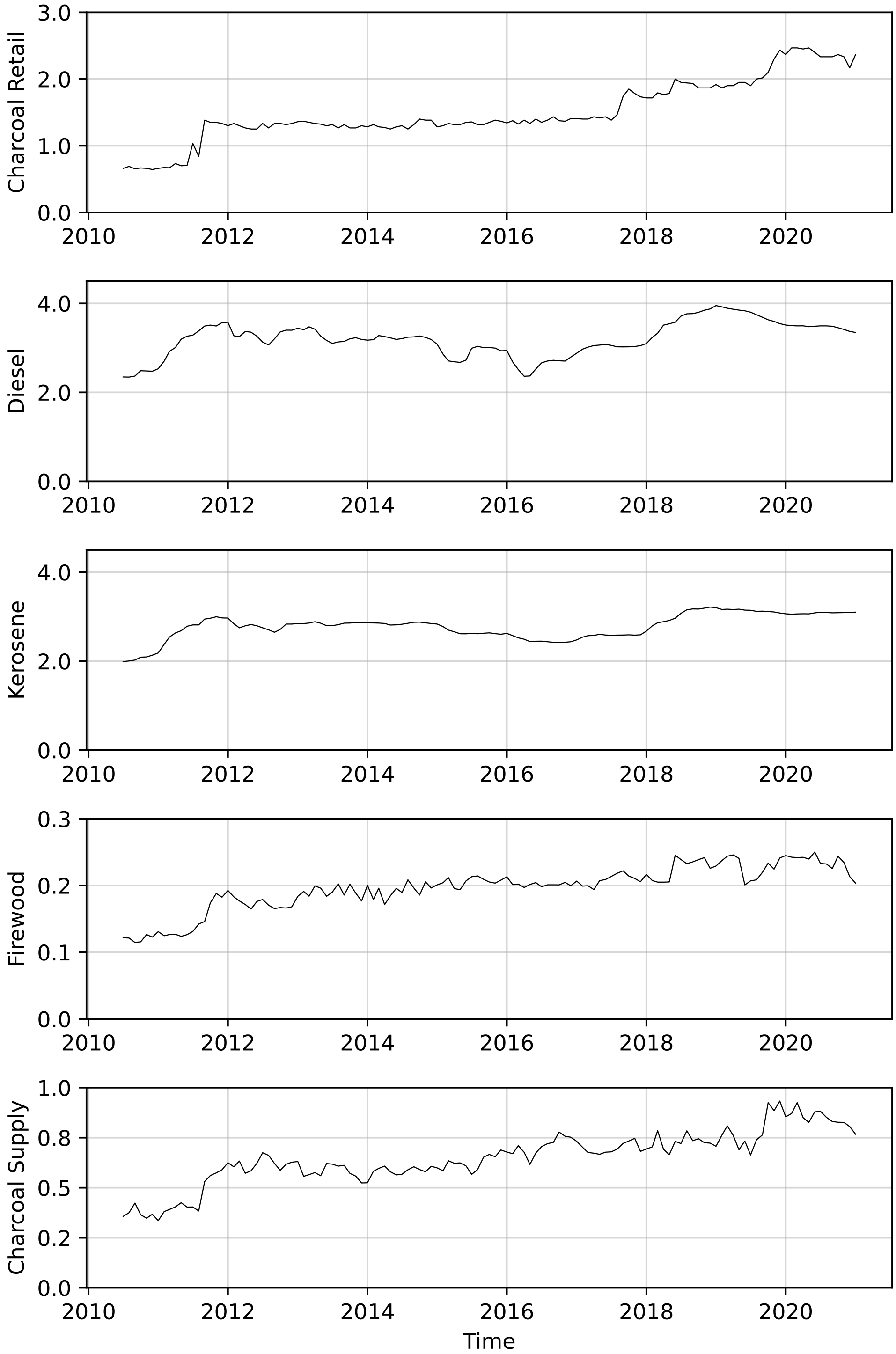


Figure 3. Nominal prices for different energy types in 1000 Ugandan Shilling (UGX). (**a**) charcoal retail price, (**b**) diesel price, (**c**) kerosene price, (**d**) firewood price, and (**e**) supply price for charcoal.

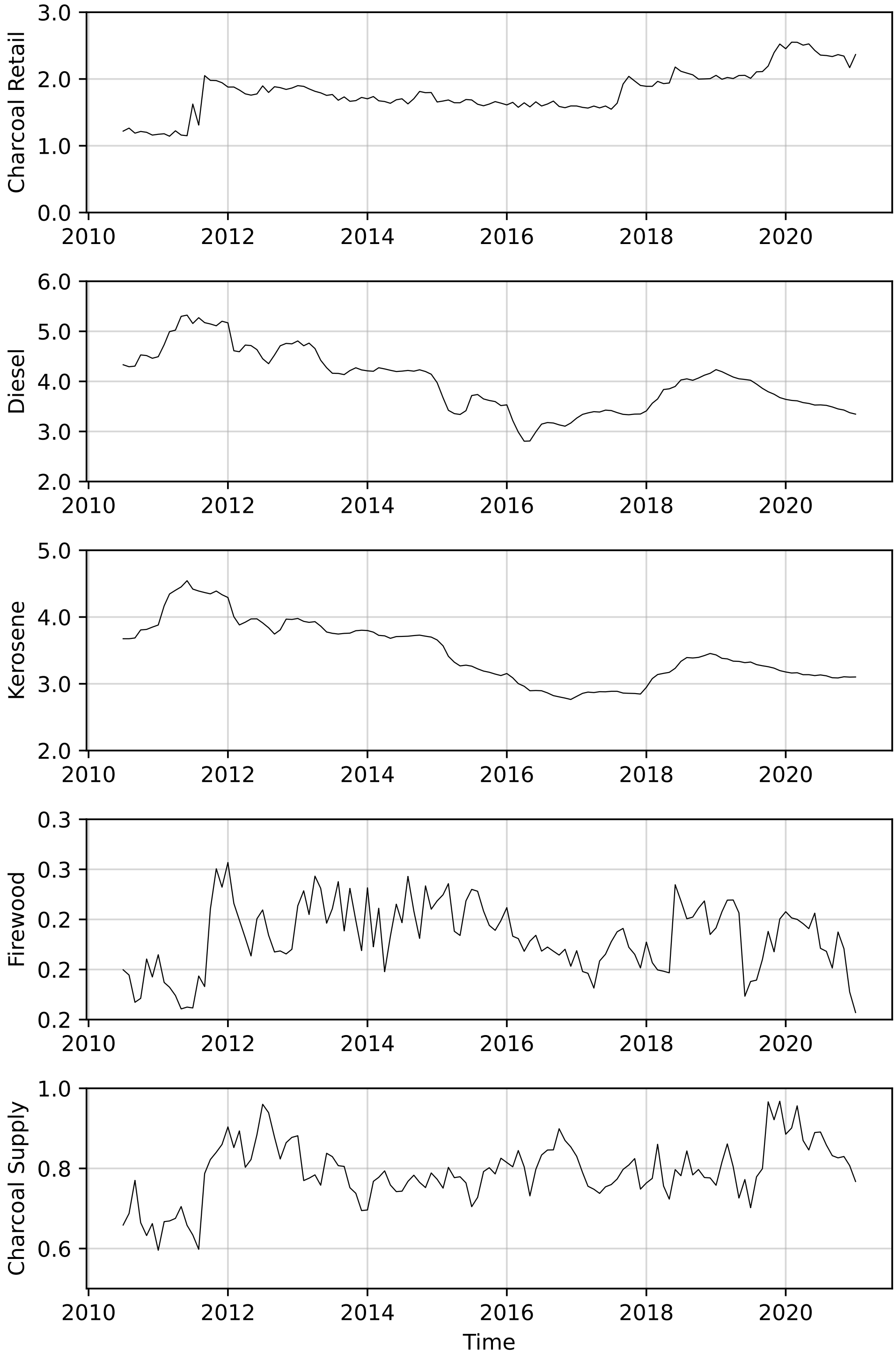


Figure 4. Real prices for different energy types in 1000 UGX. Deflated with CPI to 2021 values. (**a**) charcoal retail price, (**b**) diesel price, (**c**) kerosene price, (**d**) firewood price, and (**e**) supply price for charcoal.

Table 2. Summary statistics for energy prices in real UGX (2021 prices). $n = 127$.

Variable	Symbol	Mean	Std dev	Minimum	Maximum
Charcoal	p^c	1808.05	327.15	1142.84	2551.47
Diesel	p^d	3995.82	606.42	2805.42	5323.67
Kerosene	p^k	3472.11	461.25	2765.24	4544.29
Firewood	p^f	241.54	17.03	203.51	278.42
Supply	p^s	792.74	73.72	595.60	967.74

Table 3. Correlation matrix for energy prices in real UGX. $n = 127$.

Variable	Charcoal	Diesel	Kerosene	Firewood
Diesel	-0.232			
Kerosene	-0.305	0.957		
Firewood	0.272	0.030	0.068	
Supply	0.638	-0.249	-0.271	0.330

4.3. Unit Root Tests

The empirical analysis is based on the logarithmic values of the price variables (after scaling the prices with their respective means). It is not apparent from Figure 4 whether all price series are stationary or not. The stationarity of the price series is tested for with the augmented Dickey-Fuller (ADF) test, where the null hypothesis is that the time series is nonstationarity, and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test, where the null hypothesis is that the series is stationary (Hansen 2022).

Table 4. Augmented Dickey-Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests for unit root of log real prices. Lag length selection based on minimizing Akaike's Information Criteria (AIC). Sample period June 2010 to January 2021.

		ADF				KPSS		
Variable	Symbol	Lags	$\hat{\rho} - 1$	ADF	p-value	Lags	KPSS	p-value
Charcoal	$\ln p^c$	4	-0.069	-2.23	0.195	6	1.04	<0.010
Diesel	$\ln p^d$	2	-0.020	-1.33	0.616	6	1.07	<0.010
Kerosene	$\ln p^k$	5	-0.015	-1.49	0.540	6	1.29	<0.010
Firewood	$\ln p^f$	0	-0.292	-4.44	0.000	5	0.19	>0.100
Supply	$\ln p^s$	0	-0.235	-4.21	0.001	5	0.47	0.049

The results of the ADF and KPSS tests are shown in Table 4 where the lag lengths in the tests were selected by minimizing Akaike's information criteria (AIC). According to both tests, the prices for charcoal, diesel, and kerosene are non-stationary, whereas the price for firewood is stationary. The ADF test indicates that the charcoal supply price is stationary, while the KPSS test indicates that the price is borderline non-stationary with a p value of 0.049. From Table 4 the estimated correlation coefficient from the Dickey-Fuller regression is 0.765, which is well below one. Thus, we cautiously conclude that the supply price is stationary. The first differences in the prices of charcoal, diesel, and kerosene are stationary. Thus, the prices for charcoal, diesel and kerosene are integrated of order one ($I(1)$), while the prices for firewood and charcoal supply are integrated of order zero ($I(0)$).

4.4. Empirical Framework

Standard econometric tools to analyze price transmission and market integration are based on the idea of cointegration (Engle and Granger 1987; Fackler and Goodwin 2001; McNew 1996; von Cramon-Taubadel 2017). Market integration is the degree to which demand and supply shocks that arise in one location are transmitted to other locations (Fackler and Goodwin 2001). Therefore, in a competitive charcoal market with a supply chain that tends toward equilibrium by eliminating arbitrage opportunities, we expect the price of charcoal and other prices to be cointegrated (Engle and Granger 1987; McNew 1996). Our empirical modeling framework for analyzing price transmission follows to a large extent the discussions in Rapsomanikis et al. (2006) and Menegaki (2019).

The general autoregressive distributed lag ARDL(r,q) model for a series p_t that is a function of r lags of its own past values and current and q lags of an explanatory variable x_t (or a vector of explanatory variables) can be written as:

$$p_t = \alpha_0 + \sum_{i=1}^{r} \alpha_i p_{t-i} + \sum_{i=0}^{q} \beta_i x_{t-i} + \varepsilon_t \tag{6}$$

where ε_t is an independent and identically distributed error term. The dependent variable here is the retail price of charcoal, which is a non-stationary variable, and the explanatory variables are a mixture of $I(0)$ and $I(1)$ variables. If the variables in equation (6) are cointegrated, we can write the long-run relationship between them as:

$$p_t = \psi_0 + \psi_1 x_t + \psi_2 T_t + \nu_t \tag{7}$$

where we have added a deterministic time trend T to the model and ν_t is an independent and identically distributed error term. This error term is stationary if p and x are cointegrated. The Engle-Granger test for cointegration is a test for stationarity of the residuals from the regression model in equation (7). However, if the explanatory variables in the long-run equation are a mixture of $I(0)$ and $I(1)$ variables, as is the case here, the preferred test is the bounds test by Pesaran et al. (2001).

When p and x are cointegrated the ARDL model in equation (6) can be reparameterized as an error correction model:

$$\Delta p_t = \delta_0 - \gamma(p_{t-1} - \psi_1 x_{t-1} - \psi_2 T_t) + \sum_{i=1}^{r-1} \alpha_i \Delta p_{t-i} + \sum_{i=0}^{q-1} \beta_i \Delta x_{t-i} + \varepsilon_t \tag{8}$$

where the lag lengths r and q are sufficiently long to make the model dynamically complete. Rewrite this equation to get the unconstrained form of the error correction model:

$$\Delta p_t = \delta_0 + \theta_0 p_{t-1} + \theta_1 x_{t-1} + \theta_2 T_t + \sum_{i=1}^{r-1} \alpha_i \Delta p_{t-i} + \sum_{i=0}^{q-1} \beta_i \Delta x_{t-i} + \varepsilon_t \tag{9}$$

The ARDL bounds test is a Wald, or F-test, of the restriction $\theta_0 = \theta_1 = 0$ on the parameters in equation (9). The null hypothesis is that there is no cointegration. Rejection of the null hypothesis suggests the presence of a cointegration relationship. Furthermore, a t-test of the hypothesis that $\theta_0 = 0$ versus the alternative that $\theta_0 < 0$ which suggests cointegration. The distributions for these two tests are nonstandard and approximate critical values can be found in Kripfganz and Schneider (2020).

The full error correction model specification for the reduced form of the retail charcoal price function in equation (5) to be estimated is

$$\Delta \ln p_t^c = \delta_0 - \gamma\Big(\ln p_{t-1}^c - \psi^d \ln p_{t-1}^d - \psi^k \ln p_{t-1}^k - \psi^f \ln p_{t-1}^f - \psi^s \ln p_{t-1}^s - \psi^T T_(t-1)\Big) + \sum_{j=1}^{r-1} \alpha_j^c \Delta \ln p_{t-j}^c + \sum_{j=0}^{q_d-1} \beta_j^d \Delta \ln p_{t-j}^d + \sum_{j=0}^{q_k-1} \beta_j^k \Delta \ln p_{t-j}^k + \sum_{j=0}^{q_f-1} \beta_j^f \Delta \ln p_{t-j}^w + \sum_{j=0}^{q_s-1} \beta_j^s \Delta \ln p_{t-j}^s + \varepsilon_t. \quad (10)$$

The length of the autoregressive part is r, and the lengths of the distributed lags are denoted by q_p, q_k, q_f and q_s for diesel, kerosene, firewood and supply prices, respectively. This corresponds to an ARDL(r, q_d, q_k, q_f, q_s) model.

5. Results and Discussion

The estimated parameters for the error correction model parameterization of the ARDL model are reported in Table 5. Schwartz's Bayes Information Criteria (BIC) were used to select lag lengths in the model, resulting in an ARDL(4,0,1,0,0) model. The BIC tends to favor a more parsimonious model specification than the AIC, thus reducing the risk of overfitting.

Table 5. Long and short run estimation results for the error correction model. Sample period June 2010 to January 2021.

		Full model				Reduced model			
	Variable	Parameter	Std Err	t-value	p-value	Parameter	Std Err	t-value	p-value
Long run results	$\ln p_t^d$	0.2600	0.3417	0.76	0.448				
	$\ln p_t^k$	0.5922	0.4456	1.33	0.187	0.8791	0.1694	5.19	0.000
	$\ln p_t^f$	-0.1704	0.2710	-0.63	0.531				
	$\ln p_t^s$	0.7437	0.1875	3.97	0.000	0.7105	0.1697	4.19	0.000
	trend	0.5040	0.0698	7.22	0.000	0.5176	0.0638	8.11	0.000
Short run results	$\Delta \ln p_{t-1}^k$	-0.6696	0.3294	-2.03	0.044	-0.5615	0.3105	-1.81	0.073
	$\Delta \ln p_{t-1}^c$	-0.2224	0.0886	-2.51	0.013	-0.2110	0.0876	-2.41	0.018
	$\Delta \ln p_{t-2}^c$	0.2443	0.0891	2.74	0.007	0.2561	0.0880	2.91	0.004
	$\Delta \ln p_{t-3}^c$	0.2263	0.0848	2.67	0.009	0.2406	0.0833	2.89	0.005
	constant	-0.3484	0.5311	-0.66	0.513	-0.4287	0.5224	-0.82	0.414
EC	γ	-0.3307	0.0695	-4.76	0.000	-0.3473	0.0634	-5.48	0.000

The ARDL bounds test statistics are reported in Table 6. Both the F-test and the t-test are statistically significant at the 5% level, and we conclude that the price variables are cointegrated. The model specification is dynamically complete as Breusch-Godfrey LM-tests fail to reject the null hypothesis of no serial correlation for all lags from one to four. The Breusch-Pagan LM-test for heteroskedasticity rejects the null hypothesis of homoskedasticity. Thus, the estimated standard errors reported in Table 5 are not correct and care should be taken when drawing inference.

The estimated error correction parameter γ is statistically significant and negative. In the long-run part of the error correction model, the trend is positive and statistically significant. The parameters on the price of kerosene and the charcoal supply price are both positive and significant. The estimated parameters for the prices of diesel and firewood are clearly not statistically significant.

Table 5 also includes the parameter estimates for a reduced ARDL model in which the diesel and firewood price variables have been excluded. Parameter estimates are close to those for the full model specification. Only the parameter for the kerosene price changes noticeably and now has a much smaller standard error. The ARDL bounds test indicates that the price variables are cointegrated, and the Breusch-Godfrey LM-tests indicate that the model is dynamically complete. However, the residuals are still heteroskedastic.

Table 6. Test statistics for the ARDL models in Table 5. Sample period June 2010 to January 2021.

	Full model		Reduced model	
Test	Statistics	*p*-value	Statitstics	*p*-value
ARDL F-test	5.370	0.007	7.834	0.001
ARDL t-test	-4.760	0.019	-5.476	0.001
Breusch-Godfrey AR(1)	1.371	0.242	2.292	0.130
AR(2)	4.063	0.131	3.881	0.144
AR(3)	4.342	0.227	4.050	0.256
AR(4)	5.556	0.235	4.534	0.339
Breusch-Pagan	27.23	0.000	26.62	0.000

The estimated error correction coefficient is -0.33 for the full model and -0.35 for the reduced model. Thus, about a third of the deviation from the long-run equilibrium price is corrected for between months. The short-run model for both the full and the reduced specification includes three autoregressive terms, indicating that a short-term dynamic adjustment process is taking place for the market price of charcoal.

Charcoal prices in Kampala increased by more than 55% between June and September 2011. This transition was not smooth, but with a large increase in July (+ 35%), a decrease in August (- 22%), and a final increase in September (+ 45%). This large and concentrated price volatility could influence, in particular, the dynamics of the short-run model, contribute towards the heteroskedasticity of the residuals, and potentially result in unstable parameter estimates. The cumulative sum of the recursive residuals (CUSUM) test statistics for parameter stability in the reduced model in Table 5 is 1.63, which is higher than the critical value of 1.14 at the 1% significance level. Figure 5 shows the graph of recursive CUSUM along with a 95% confidence band.

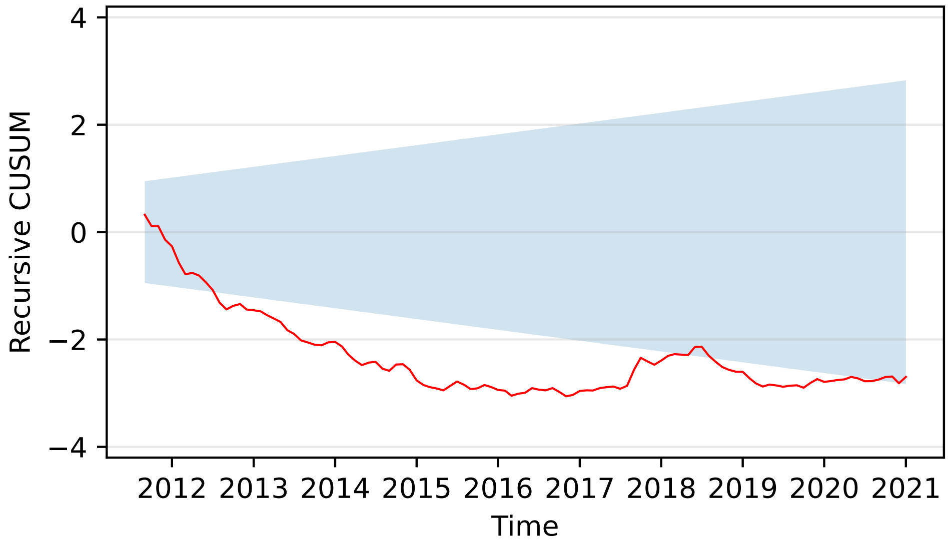


Figure 5. Recursive CUSUM plot with 95% confidence bands around the null for the reduced error correction model. Sample period June 2010 to January 2021.

The results of the CUSUM test is evidence of structural breaks in one or more of the prices series. Using a sample period starting after the sharp increase in prices between July and September 2011, Table 7 shows the results of the ADF and KPSS tests where the lag lengths in the tests were selected by minimizing the AIC. The results are unchanged from those for the longer period with charcoal, diesel, and kerosene prices being $I(1)$ variables, and firewood and charcoal supply prices being $I(0)$ variables.

Table 7. Augmented Dickey-Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests for unit root of log real prices. Lag length selection based on minimizing Akaike's Information Criteria (AIC). Sample period September 2011 to January 2021.

		ADF				KPSS		
Variable	Symbol	Lags	$\hat{\rho}-1$	ADF	p-value	Lags	KPSS	p-value
Charcoal	$\ln p^c$	0	-0.025	-0.96	0.767	6	0.85	<0.010
Diesel	$\ln p^d$	7	-0.030	-1.92	0.321	6	0.82	<0.010
Kerosene	$\ln p^k$	1	-0.021	-2.08	0.253	6	1.08	<0.010
Firewood	$\ln p^f$	1	-0.342	-3.77	0.003	5	0.61	0.022
Supply	$\ln p^s$	0	-0.296	-4.36	0.000	5	0.21	>0.100

Estimating both the full and the reduced error correction model with observations from September 2011 onward and using BIC to select the lag length results in an ARDL(1,0,0,0,0) and an ARDL(1,0,0) specification, respectively, and the results are reported in Table 8. The ARDL bounds tests, Table 9, are inconclusive with respect to cointegration in the full model specification. The reduced model specification has cointegration between the retail and supply prices for charcoal and kerosene price. The models are dynamically complete with homoskedastic errors. The models do not include any autoregressive terms. The three autoregressive terms included in the models in Table 5 were probably related to the three months with high price volatility in 2011.

Table 8. Long and short run estimation results for the error correction model. Sample period September 2011 to January 2021.

		Full model				Reduced model			
	Variable	Parameter	Std Err	t-value	p-value	Parameter	Std Err	t-value	p-value
Long run results	$\ln p_t^d$	0.1623	0.2972	0.55	0.586				
	$\ln p_t^k$	0.6896	0.4177	1.65	0.102	0.8473	0.1716	4.94	0.000
	$\ln p_t^f$	-0.1756	0.2695	-0.65	0.516				
	$\ln p_t^s$	0.5020	0.1983	3.63	0.000	0.7165	0.1988	3.60	0.000
	trend	0.5020	0.0657	7.64	0.000	0.5165	0.0629	8.21	0.000
Short run results	constant	0.0506	0.3693	0.14	0.891	-0.0498	0.3458	-0.14	0.886
EC	γ	-0.2322	0.0560	-4.15	0.000	-0.2300	0.0556	-4.13	0.000

Table 9. Test statistics for the ARDL models in Table 8. Sample period September 2011 to January 2021.

	Full model		Reduced model	
Test	Statistics	p-value	Statitstics	p-value
ARDL F-test	3.544	0.112	5.159	0.029
ARDL t-test	-4.145	0.082	-4.135	0.036
Breusch-Godfrey AR(1)	0.017	0.897	0.027	0.870
AR(2)	0.420	0.811	0.173	0.918
Breusch-Pagan	2.30	0.130	2.53	0.112

The recursive CUSUM test statistic for the reduced model is 0.648, which is less than the 10% critical value at 0.850. The plot of the recursive CUSUM along with a 95% confidence band is shown in Figure 6. Thus, the parameters remain stable during this shorter sample period.

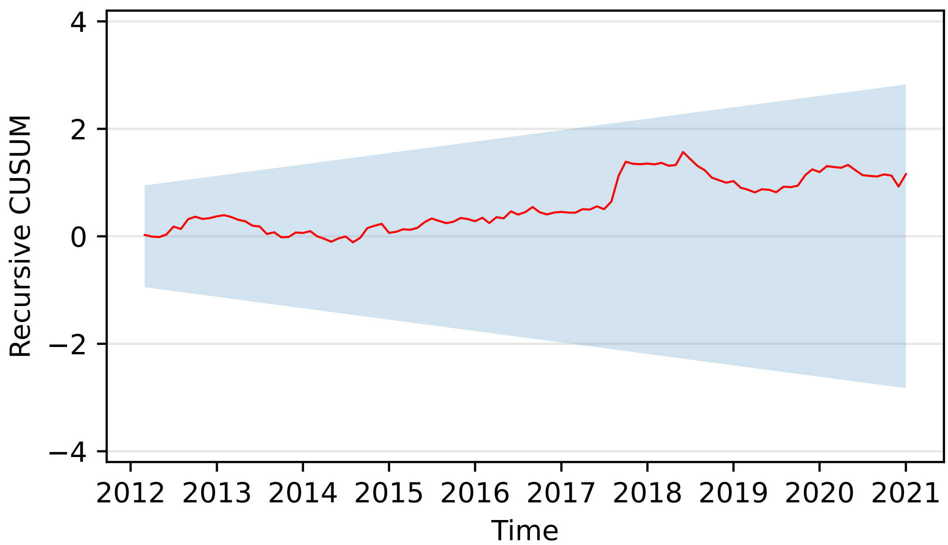


Figure 6. Recursive CUSUM plot with 95% confidence bands around the null for the reduced error correction model. Sample period September 2011 to January 2021.

In the period after the sharp increase in nominal and real prices in 2011, our econometric analysis shows that the retail and supply prices of charcoal, and kerosene prices are co-integrated, i.e., there exists a long-term relationship between these prices. The long-term link between prices along a supply chain from source to retail is expected as these prices adjust to reflect changing supply and demand conditions. There are no statistically significant autoregressive or distributed lag terms in the estimated model, reflecting a lack of short-term dynamics in the retail price beyond the long-term equilibrium correction. This implies that it is not possible to test for Granger causality in this model (Enders 2014).

The trend variable has a statistically significant positive parameter value. Increasing demand from a growing urban population and reduced supply from deforestation are trends that will increase the equilibrium price of charcoal, which we observe.

The simple correlation between the retail price of charcoal and the price of kerosene (and diesel) is negative (Table 3) as can be seen in Figure 4. However, the results of the ARDL model show a positive long-term relationship between the retail prices of charcoal and kerosene. The price of kerosene, which is an imported petrol product, will reflect world market conditions. An increase in kerosene price would see households substituting from kerosene to charcoal, hence increasing demand and the equilibrium price for charcoal. The absence of a short-term link between kerosene and charcoal prices suggests that there is limited short-term substitution between charcoal and kerosene. This result would be consistent with the short-term lock in effects related to household investments required in new cookstove equipment required to change cooking fuel types.

6. Conclusions

Charcoal is the dominant energy source in urban areas in Uganda, as is the case in many countries in sub-Sahara Africa. The Walk-to-Work protests in 2011 came at a time of high inflation and sharply increasing prices for charcoal and petroleum products. Retail prices are expected to reflect prices, costs, and market conditions along the supply chain. In functioning markets, these prices tend to be in long-term equilibrium. We used monthly price data to test for cointegration in an error-correction model. As the price data are integrated of order zero and one, the ARDL bounds test is used. We find that there is a long-term relationship between the retail price of charcoal and the supply price of charcoal and kerosene (which is a substitute energy source for the end users). Firewood and diesel prices are not statistically significant in the model. The long-term equation includes a positive trend, indicating that the retail price of charcoal is increasing more over time than would be implied by the supply price of charcoal and the price of kerosene. The specific reasons for this increase in retail prices are not possible to determine with the available data.

Our analysis shows that prices along the supply chain tend to be in long-term equilibrium. Therefore, policies that affect the supply and/or demand sides of charcoal will have ripple effects throughout the chain. Different possible causes of the positive time trend in our model have different policy implications. As discussed in Rose et al. (2022) and Mensah et al. (2022), the continued growth of urban populations will keep the demand for charcoal high and put further pressure on the supply chain. Improved forest management and replanting are important to maintain supply volume. However, as argued by Mensah et al. (2022), there is room for technical improvements in the small-scale production of charcoal.

Another possible reason for the upward trend in charcoal prices could be an increase in transportation costs as a result of the increased time used for transportation, everything else constant. Kampala, as many other African cities, is experiencing severe traffic congestion leading to long delays. The lockdown and traffic restrictions imposed during the Covid-19 pandemic may serve as a natural experiment to test the effect of traffic congestion on charcoal prices.

With only price data available, we are limited in our analysis of spatial equilibria and price patterns. Additional price data, say, from sources similar to the CPI base data used here, with spatial information would allow for more detailed analysis of the spatial patterns of price linkages and price change transmissions. This could also open the possibility for a more detailed analysis of transportation costs and supply side issues. As several countries are implementing different charcoal policies, including production bans, the analysis of cross-border effects is relevant for understanding domestic price changes. Another venue could be to explore the margins along the supply chain to better understand how competitive the different segments are and whether there may be excessive margins due to the structure of the market.

Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey-Fuller
AIC	Akaike's information criteria
ARDL	Autoregressive distributed lag
BIC	Schwartz's Bayesian information criteria
CPI	Consumer price index
CUSUM	Cumulative sum of recursive residuals
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
UBOS	Uganda Bureau of Statistics
UGX	Ugandan Shilling

Author Contributions: Conceptualization, G.A. and O.B.; methodology, G.A. and O.B.; formal analysis, G.A. and O.B.; data curation, G.A.; writing – original draft preparation, G.A.; writing – review and editing, G.A. and O.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Norwegian Programme for Capacity Building in Higher Education and Research for Development (NORHED), project number: QZA-0486-13/0017.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study is available from the corresponding author upon request.

Acknowledgments: The authors gratefully acknowledge Alan Love and Benard Musekese Wabukala for their comments and suggestions on earlier versions of this article. The authors thank the anonymous reviewers for their constructive comments.

Conflicts of Interest: The authors declare no conflict of interest.

References

Aarakit, S. M., V. F. Ssennono, and M. S. Adaramola. 2021. Estimating market potential for solar photovoltaic systems in Uganda. *Frontiers in Energy Research 9*, 602468. https://doi.org/10.3389/fenrg.2021.602468.

Acosta, A., R. Ihle, and S. von Cramon-Taubadel. 2021. Combining market structure and econometric methods for price transmission analysis. *Food Security 11*(4), 941–951. https://doi.org/10.1007/s12571-019-00951-w.

Agbugba, I. K. and A. Obi. 2013. Market structure, price formation and price transmission for wood charcoal in Southeastern Nigeria. *Journal of Agricultural Science 5*(10), 77–86. https://doi.org/10.5539/jas.v5n10p.

Agyei, F. K., C. Pilegaard Hansen, and E. Acheampong. 2018. Profit and profit distribution along Ghana's charcoal commodity chain. *Energy for Sustainable Development 47*, 62–74. https://doi.org/10.1016/j.esd.2018.09.002.

Alonso, W. 1964. *Location and Land Use: Toward a General Theory of Land Rent*. Cambridge, MA: Harvard University Press. https://doi.org/10.4159/harvard.9780674730854.

Arnold, J. E. M., G. Köhlin, and R. Persson. 2006. Woodfuels, livelihoods, and policy interventions: Changing perspectives. *World Development 34*(3), 596–611. https://doi.org/10.1016/j.worlddev.2005.08.008.

Barboza Martignone, G., K. Behrendt, and D. Paparas. 2022. Price transmission analysis of the international soybean market in a trade war context. *Economies 10*(8). https://doi.org/10.3390/economies10080203.

Barrett, C. B. 1996. Market analysis methods: Are our enriched toolkits well suited to enlivened markets? *American Journal of Agricultural Economics 78*(3), 825–829. https://doi.org/10.2307/1243313.

Baumert, S., A. C. Luz, J. Fisher, F. Vollmer, C. M. Ryan, G. Patenaude, P. Zorrilla-Miras, L. Artur, I. Nhantumbo, and D. Macqueen. 2016. Charcoal supply chains from Mabalane to Maputo: Who benefits? *Energy for Sustainable Development 33*, 129–138. https://doi.org/10.1016/j.esd.2016.06.003.

Branch, A., F. K. Agyei, J. G. Anai, S. T. Apecu, A. Bartlett, E. Brownell, M. Caravani, C. J. Cavanagh, S. Fennell, S. Langole, M. B. Mabele, T. H. Mwampamba, M. Njenga, A. Owor, J. Phillips, and N. Tiitmamer. 2022. From crisis to context: Reviewing the future of sustainable charcoal in Africa. *Energy Research and Social Science 87*, 102457. https://doi.org/10.1016/j.erss.2021.102457.

Brobbey, L. K., M. Pouliot, C. Pilegaard Hansen, and B. Kyereh. 2019. Factors influencing participation and income from charcoal production and trade in Ghana. *Energy for Sustainable Development 50*, 69–81. https://doi.org/10.1016/j.esd.2019.03.003.

Chidumayo, E. N. and D. J. Gumbo. 2013. The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis. *Energy for Sustainable Development 17*(2), 86–94. https://doi.org/10.1016/j.esd.2012.07.004.

D'Agostino, A. L., J. Urpelainen, and A. Xu. 2015. Socio-economic determinants of charcoal expenditures in Tanzania: Evidence from panel data. *Energy Economics 49*, 472–481. https://doi.org/10.1016/j.eneco.2015.03.007.

Doggart, N., R. Ruhinduka, C. K. Meshack, R. C. Ishengoma, T. Morgan-Brown, J. M. Abdallah, D. V. Spracklen, and S. M. Sallu. 2020. The influence of energy policy on charcoal consumption in urban households in Tanzania. *Energy for Sustainable Development 57*, 200–213. https://doi.org/10.1016/j.esd.2020.06.002.

Enders, W. 2014. *Applied Econometric Time Series*. Wiley series in probability and statistics. Wiley.

Engle, R. F. and C. W. J. Granger. 1987. Co-integration and error correction: Representation, estimation, and testing. *Econometrica 55*(2), 251–276. https://doi.org/10.2307/1913236.

Fackler, P. L. and B. K. Goodwin. 2001. Spatial price analysis. In B. L. Gardner and G. C. Rausser (Eds.), *Marketing, Distribution and Consumers*, Volume 1 of *Handbook of Agricultural Economics*, pp. 971–1024. Elsevier. https://doi.org/10.1016/S1574-0072(01)10025-3.

Fujita, M. 1989. *Urban Economic Theory: Land Use and City Size*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511625862.

Graubner, M., K. Salhofer, and C. Tribl. 2021. A line in space: Pricing, location, and market power in agricultural product markets. *Annual Review of Resource Economics 13*(1), 85–107. https://doi.org/10.1146/annurev-resource-110220-010922.

Hansen, B. E. 2022. *Econometrics*. Princeton, NJ: Princeton University Press.

Haysome, S., M. McLaggan, J. Kaka, L. Modi, and K. Opala. 2021. *Black Gold - The charcoal grey market in Kenya, Uganda and South Sudan*. Geneva: The Global Initiative Against Transnational Organized Crime.

Hofstad, O. 1997. Woodland deforestation by charcoal supply to Dar es Salaam. *Journal of Environmental Economics and Management 33*(1), 17–32. https://doi.org/10.1006/jeem.1996.0975.

Hofstad, O. and P. L. Sankhayan. 1999. Prices of charcoal at various distances from Kampala and Dar es Salaam 1994–1999. *Southern African Forestry Journal 186*(1), 15–18. https://doi.org/10.1080/10295925.1999.9631237.

Hosier, R.H and W Kipondya. 1993. Urban household energy use in Tanzania: Prices, substitutes and poverty. *Energy Policy 21*(5), 454–473. https://doi.org/10.1016/0301-4215(93)90035-E.

Huffaker, R., G. Griffith, C. Dambui, and M. Canavari. 2021. Empirical detection and quantification of price transmission in endogenously unstable markets: The case of the global–domestic coffee supply chain in Papua New Guinea. *Sustainability 13*(16). https://doi.org/10.3390/su13169172.

IEA. 2023. Uganda 2023. Energy policy review, International Energy Agency, Paris.

Khundi, F., P. Jagger, G. Shively, and D. Sserunkuuma. 2011. Income, poverty and charcoal production in Uganda. *Forest Policy and Economics 13*(3), 199–205. https://doi.org/10.1016/j.forpol.2010.11.002.

Kripfganz, Sebastian and Daniel C. Schneider. 2020. Response surface regressions for critical value bounds and approximate p-values in equilibrium correction models1. *Oxford Bulletin of Economics and Statistics 82*(6), 1456–1481. https://doi.org/10.1111/obes.12377.

Masera, O. R., R. Bailis, R. Drigo, A. Ghilardi, and I. Ruiz-Mercado. 2015. Environmental burden of traditional bioenergy use. *Annual Review of Environment and Resources 40*(1), 121–150. https://doi.org/10.1146/annurev-environ-102014-021318.

McNew, K. 1996. Spatial market integration: Definition, theory, and evidence. *Agricultural and Resource Economics Review 25*(1), 1–11. https://doi.org/10.1017/S1068280500000010.

MEMD. 2016. National charcoal survey for Uganda 2015. Final report, Ministry of Energy and Mineral Development, Kampala, Uganda.

MEMD. 2023. Energy policy policy for Uganda 2023. Technical report, Ministry of Energy and Mineral Development, Kampala, Uganda.

Menegaki, A. N. 2019. The ARDL method in the energy-growth nexus field; best implementation strategies. *Economies 7*(4). https://doi.org/10.3390/economies7040105.

Mensah, K. E., L. Damnyag, and N. S. Kwabena. 2022. Analysis of charcoal production with recent developments in sub-Sahara Africa: A review. *African Geographical Review 41*(1), 35–55. https://doi.org/10.1080/19376812.2020.1846133.

Monela, G. C., E. Zahabu, R. E. Malimbwi, G. Jambiya, and S. Misana. 2007. Socio-economics of charcoal extraction in Tanzania: A case of eastern part of Tanzania. CHAPOSA.

Mutyaba, M. 2022. From voting to walking: The 2011 Walk-to-Work protest movement in Uganda. In E. Rodrigues Sanches (Ed.), *Popular Protest, Political Opportunities, and Change in Africa*, pp. 163–180. London: Routledge.

Nyamoga, G. Z., H. K. Sjølie, G. Latta, Y. M. Ngaga, R. Malimbwi, and B. Solberg. 2022. Effects of income and price on household's charcoal consumption in three cities of tanzania. *International Journal of Forestry Research 2022*, 9988979. https://doi.org/10.1155/2022/9988979.
Nyamoga, G. Z. and B. Solberg. 2019. A review of studies related to charcoal production, consumption, and greenhouse gas emissions in Tanzania. In Y. Bamutaze, S. Kyamanywa, B. R. Singh, G. Nabanoga, and R. Lal (Eds.), *Agriculture and Ecosystem Resilience in Sub Saharan Africa: Livelihood Pathways Under Changing Climate*, pp. 357–399. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-12974-3_17.
Nzabona, A., R. Tuyiragize, J. B. Asiimwe, C. Kakuba, and P. Kisaakye. 2021. Urban household energy use: Analyzing correlates of charcoal and firewood consumption in Kampala City, Uganda. *Journal of Environmental and Public Health 2021*, 5904201. https://doi.org/10.1155/2021/5904201.
Olabisi, M., D. L. Tschirley, D. Nyange, and T. Awokuse. 2019. Energy demand substitution from biomass to imported kerosene: Evidence from Tanzania. *Energy Policy 130*, 243–252. https://doi.org/10.1016/j.enpol.2019.03.060.
Pesaran, M. H., Y. Shin, and R. J. Smith. 2001. Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics 16*(3), 289–326. https://doi.org/10.1002/jae.616.
Poblete-Cazenave, M. and S. Pachauri. 2018. A structural model of cooking fuel choices in developing countries. *Energy Economics 75*, 449–463. https://doi.org/10.1016/j.eneco.2018.09.003.
Randall, A. and E. N. Castle. 1985. Land resources and land markets. In A. V. Kneese and J. L. Sweeney (Eds.), *Handbook of Natural Resource and Energy Economics*, Volume 2, pp. 571–620. Amsterdam: North-Holland. https://doi.org/10.1016/S1573-4439(85)80020-8.
Rapsomanikis, G., D. Hallam, P. Conforti, and A. H. Sarris. 2006. Market integration and price transmission in selected food and cash crop markets of developing countries: review and applications. In *Commodity Market Review, 2003–2004*, Rome. FAO.
Roman, M. and Z. Žáková Kroupová. 2022. Spatial market integration: A case study of the Polish–Czech milk market. *Economies 10*(1). https://doi.org/10.3390/economies10010025.
Rose, J., G. Bensch, A. Munyehirwe, and J. Peters. 2022. The forgotten coal: Charcoal demand in Sub-Saharan Africa. *World Development Perspectives 25*, 100401. https://doi.org/10.1016/j.wdp.2022.100401.
Sander, K., C. Gros, and C. Peter. 2013. Enabling reforms: Analyzing the political economy of the charcoal sector in Tanzania. *Energy for Sustainable Development 17*, 116–126. https://doi.org/10.1016/j.esd.2012.11.005.
Sankhayan, P. L. and O. Hofstad. 2000. Production and spatial price differences for charcoal in uganda. *Journal of Forest Research 5*(3), 117–121. https://doi.org/10.1007/BF02762389.
Schure, J., V. Ingram, M. S. Sakho-Jimbira, P. Levang, and K. F. Wiersum. 2013. Formalisation of charcoal value chains and livelihood in Central- and West Africa. *Energy for Sustainable Development 17*(2), 95–105. https://doi.org/10.1016/j.esd.2012.07.002.
Shively, G., P. Jagger, D. Sserunkuuma, A. Arinaitwe, and C. Chibwana. 2010. Profit and margins along Uganda's charcoal value chain. *International Forestry Review 12*(3), 270–283. https://doi.org/10.1505/ifor.12.3.270.
Ssennono, V. F., J. M. Ntayi, F. Buyinza, F. Wasswa, S. M. Aarakit, and C. N. Mukiza. 2021. Energy poverty in Uganda: Evidence from a multidimensional approach. *Energy Economics 101*, 105445. https://doi.org/10.1016/j.eneco.2021.105445.
Takayama, T. and G. G. Judge. 1971. *Spatial and Temporal Price and Allocation Models*, Volume 73 of *Contributions to Economic Analysis*. Amsterdam: North-Holland.
von Cramon-Taubadel, S. 2017. The analysis of market integration and price transmission – results and implications in an African context. *Agrekon 56*(2), 83–96. https://doi.org/10.1080/03031853.2017.1295655.
von Cramon-Taubadel, S. and B. K. Goodwin. 2021. Price transmission in agricultural markets. *Annual Review of Resource Economics 13*(1), 65–84. https://doi.org/10.1146/annurev-resource-100518-093938.
Wabukala, B. M., O. Bergland, N. Rodaheranwa, S. Watundu, M. S. Adaramola, M. Ngoma, and A. A. Rwaheru. 2022. Unbundling barriers to electricity security in Uganda: A review. *Energy Strategy Reviews 44*, 100984. https://doi.org/10.1016/j.esr.2022.100984.
Worku, A., A. Andaregie, and T. Astatkie. 2021. Analysis of the charcoal market chain in Northwest Ethiopia. *Small-scale Forestry 20*, 407–424. https://doi.org/10.1007/s11842-021-09474-9.

Paper 4

Economic Growth–Electricity Consumption Linkage in Uganda Revisited

Grace Alinaitwe[a,b] and Olvar Bergland[a,c]

[a]School of Economics and Business, Norwegian University of Life Sciences, 1432 Ås, Norway; [b]Department of Management Science, Makerere University Business School, Kampala, Uganda; [c]School of Economic Sciences, Washington State University, Pullman, WA 99161, USA

ABSTRACT

This study reexamines the relationship between electricity consumption and economic growth in Uganda using seasonally unadjusted quarterly data from 2010Q3–2023Q3. We use the perpetual inventory method to construct a time series for capital stock from the time series for investment. The time series for gross domestic product (GDP), capital stock, and electricity consumption are nonstationary. The seasonal first difference, or year-to-year change, of the series is stationary. Using the Engle-Granger cointegration test, we do not find cointegration between GDP, capital stock, and electricity consumption. A vector-autoregressive (VAR) model in seasonal differences with three lags is dynamically complete. From the Granger causality test, we find that there is no Granger causality from electricity to GDP, or vice versa, thus supporting the neutrality hypothesis. Previous studies of economic growth-electricity nexus, using data from before 2010, have found support for the feedback hypotheses where there is Granger causality in both directions between GDP and electricity consumption. We suggest that future research should focus on detecting any potential structural breaks in the GDP and electricity consumption relationship and what such a break may mean for economic growth and policy recommendations.

KEYWORDS

VAR; Granger causality; neutrality hypothesis

1. Introduction

Electricity is viewed as an essential part of economic growth at the national, local, and individual levels. Electricity serves as the basis for industrial development and improved productivity in many economic sectors, as well as facilitating and easing household activities and chores. Therefore, lack of access to electricity can have a negative impact on economic growth. Uganda has one of the lowest levels of electricity consumption in the world, with a consumption of approximately 100 kWh per year per capita in 2021 (IEA 2023). Uganda's 2040 vision is to increase its electricity generation capacity from 1 250 MW in 2021 to 52 400 MW, and increase annual electricity consumption per capita to 578 kWh (IEA 2023).

The literature presents conflicting results regarding the relationship between electricity consumption and economic growth. Ozturk (2010) suggests that the contradictory results in the literature may be due to differences in country contexts, data quality, and the econometric methods used. Policymakers should take into account the relationship between electricity consumption and economic growth when designing and implementing energy policies.

The literature on the relationship between electricity consumption and economic growth has produced conflicting results. Some studies (Gurgul and Lach 2012; Polemis and Dagoumas 2013) suggest that there is a two-way relationship between the two variables. In contrast, other researchers (Iyke 2015; Churchill and Ivanovski 2020) have found evidence of a one-way relationship, with electricity consumption driving economic growth. Shahbaz and Feridun (2012) concluded that the opposite is true, with economic growth driving electricity consumption. Furthermore, other scholars, such as Karanfil and Li (2015) and Yoo and Kwak (2010), have not found a statistical relationship between the two variables.

Studies on the relationship between electricity consumption and economic growth in Uganda have yielded similar conflicting results. Sekantsi and Okot (2016) found a long-term bidirectional relationship between electricity consumption and gross domestic product (GDP) using annual data for the period 1982–2013. Alinda et al. (2022) using annual data for the period 1986–2017 and including gross fixed capital formation as an explanatory variable find a unidirectional statistical relationship from electricity consumption to GDP. Using quarterly data for the period 2005Q1–2015Q1 Mawejje and Mawejje (2016) also reported a long-term unidirectional relationship from electricity consumption to GDP. Mutumba et al. (2022) using quarterly data for the period 2008Q1–2018Q4 and including gross capital formation in the model find support for a bidirectional Granger causality. As these studies differ substantially in their findings, their policy implications also differ.

These studies differ in several respects with respect to the time period and time resolution of the data used in their analysis. Sekantsi and Okot (2016) and Alinda et al. (2022) use annual data from the World Bank Development Indicator database. Mawejje and Mawejje (2016) are using quarterly data from the Uganda Bureau of Statistics (UBOS), while Mutumba et al. (2022) are using quarterly data obtained from the World Bank.

The upper part of Figure 1 shows (the log of) GDP per capita in constant monetary terms for Uganda, and the lower part shows the annual change. The increase in GDP per capita appears to have settled at a lower rate since about 2011. In the period up to 2012 the annual growth rate of GDP per capita was approximately 3.8%, while the growth rate is 1.3% after 2011. Published studies of the linkage between electricity consumption and GDP in Uganda use data from both of these periods. If there has been a structural change in the economy, older empirical results may not remain relevant to understanding the current relationship between electricity consumption and GDP.

The purpose of this article is to re-evaluate the relationship between electricity consumption and GDP in Uganda using more recent data. We are using quarterly data from UBOS as these data are the primary data in this context, and we avoid any currency effects inherent in the World Bank dollar based data series. Many past studies have used fixed capital formation (investment) as a proxy for fixed capital in empirical analysis. We use the perpetual inventory method to construct a time series for fixed capital, thus bringing our empirical model closer to the

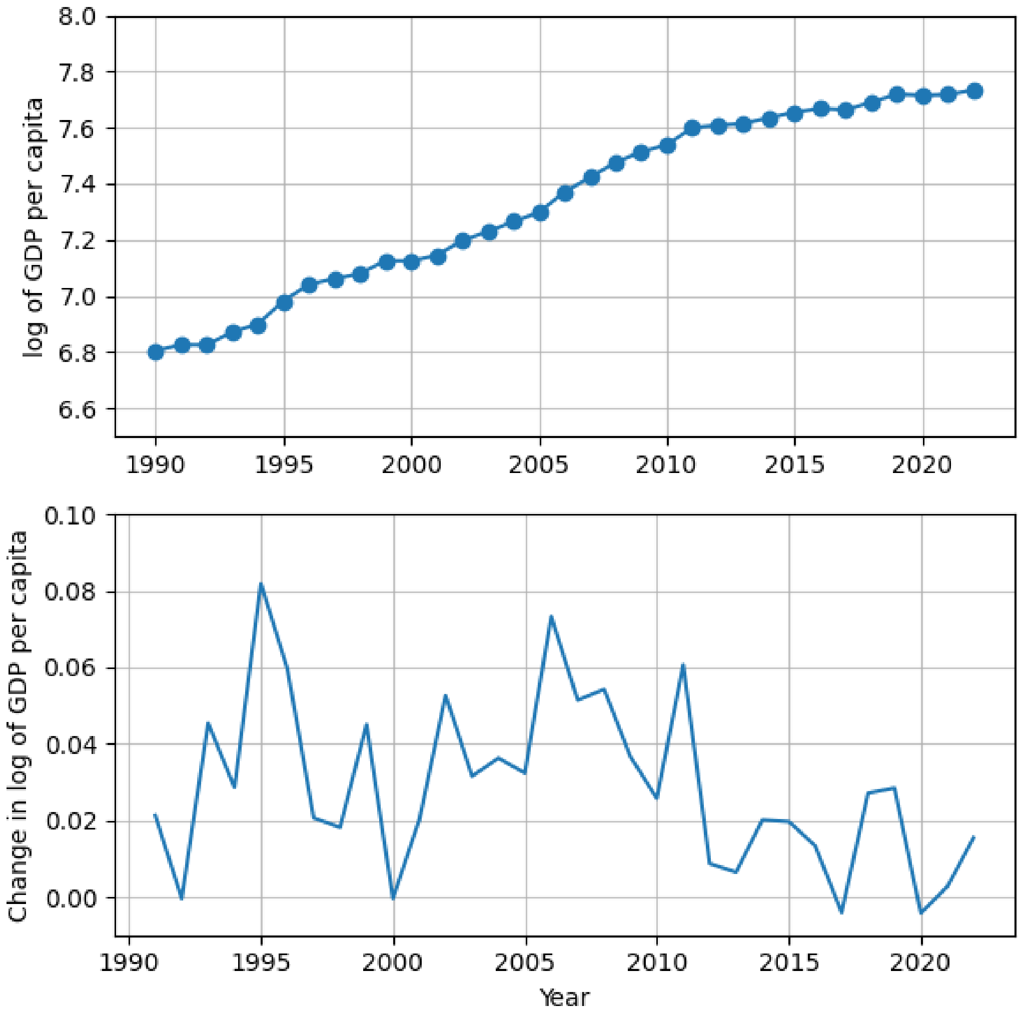


Figure 1. Annual GDP per capita and annual change in GDP per capita for Uganda, 1990–2021. Constant 2015 USD.

theoretical model. Our empirical finding of no statistical linkage between GDP and electricity consumption contributes to understanding of the energy-growth nexus by using more recent data.

The next section gives a selective review of the literature on the relationship between electricity consumption and economic growth. Section 3 describes the data that we use, as well as the statistical model and statistical tests. The empirical results are presented in Section 4 and discussed in Section 5. Section 6 concludes.

2. Literature Review

There is a vast literature investigating the relationship between electricity consumption and economic growth following the pioneering work of Kraft and Kraft (1978). They identified a unidirectional causality from the Gross National Product (GNP) to electricity consumption in the United States. Despite the numerous studies[1] on the relationship between electricity consumption and economic growth, there is no consensus on the results. However, four types of relationship between electricity consumption and economic growth can be identified: (i) the growth hypothesis (electricity consumption-led growth), (ii) the feedback hypothesis (bidirectional causality), (iii) the conservation hypothesis (growth-led electricity consumption), and (iv) the neutrality hypothesis (no causality). In this section, we present selective empirical evidence for each of these hypotheses. However, see Mutumba et al. (2021) for an exhaustive overview of the literature.

Focusing on evidence of the growth hypothesis, Lawal et al. (2020) examined the nexus between electricity consumption and economic growth in 17 sub-Saharan African countries using data from 1971 to 2017 using the system generalized method of moments (GMM) estimation technique. Researchers also control for other determinants of economic growth, such as financial development, foreign direct investment, trade, government spending, life expectancy, education, inflation, labor, savings rate, and governance effectiveness. The argument is that electric-

[1]The survey by Mutumba et al. (2021) covers 1,240 articles published in the period 1974–2021.

ity consumption and other control variables jointly determine economic growth. Their results support the growth hypothesis, which implies that electricity consumption has a positive unidirectional effect on economic growth. However, upon further examination, considering the threshold effect, the authors found that electricity consumption has a positive marginal effect on economic growth only in periods of low energy intensity. Electricity consumption has a negative marginal effect on economic growth in periods and contexts of high energy intensity. This indicates that high energy intensity leads to a waste of energy, thus negatively impacting economic growth. In general, policies that stimulate efficient electricity consumption should be promoted to enhance sustainable economic growth.

Similarly, Churchill and Ivanovski (2020) found that electricity consumption at the state level is positively related to economic growth in Australia. The study uses panel data from 1990 to 2015 and controls for labor and capital. Moreover, Iyke (2015) found a positive unidirectional relationship from electricity consumption to economic growth in Nigeria using the Vector Error Correction Model (VECM) and employing data covering a period from 1971 to 2011. The study controls for inflation.

Similarly, Yoo and Kwak (2010) found a positive unidirectional causality from electricity consumption to economic growth in Argentina, Brazil, Chile, Columbia and Ecuador using the Granger causality technique with data for 1975-2006. These studies suggest that such economies should enhance the generation and consumption of electricity to boost economic growth. Furthermore, the adoption of energy conservation policies should be avoided, as they will negatively impact economic growth. Furthermore, Samu, Bekun, and Fahrioglu (2019) examined the relationship between electricity consumption, real gross domestic product per capita, and carbon dioxide emissions in Zimbabwe using data from 1971–2014, employing the Maki cointegration test and the Toda-Yamamoto causality test. They found support for the hypothesis of electricity-led growth. This suggests that energy conservation policies may harm Zimbabwe's economic growth; hence, the country should diversify its energy portfolio to promote economic growth.

Regarding the feedback hypothesis (bidirectional), Polemis and Dagoumas (2013) conducted a study using data from 1970 to 2011 for Greece, employing the cointegration technique and the vector error correction model and controlling for other variables such as employment and the price of electricity in their model. The results supported a bidirectional causality between electricity consumption and economic growth. Similar findings of bidirectional causality were reported in Poland Kasperowicz (2014). This author obtained results indicating a bidirectional causality between electricity consumption and economic growth in Poland using 2000-2012 data, employing the Granger causality technique and Ordinary Least Squares (OLS) model estimations, and controlling for capital and employment. Furthermore, Hamdi, Sbia, and Shahbaz (2014) found a bidirectional causality between electricity consumption and economic growth in Bahrain. Their study used quarterly data from 1980 to 2010, applying the autoregressive distributed lag (ARDL) technique and Granger causality approach while controlling for capital and foreign direct investment.

Osman, Gachino, and Hoque (2016) explored the electricity consumption-economic growth relationship in the Gulf Cooperation Council (GCC) countries using data from 1975 to 2012. They used the panel VAR Granger causality test, controlled for gross capital formation, and obtained support for the feedback hypothesis. Furthermore, Ogundipe and Apata (2013) found support for the feedback hypothesis in Nigeria. They used VECM and Granger causality techniques and data covering the period of 1980 to 2008 while controlling for labor and capital. The results of Karanfil and Li (2015) support a bidirectional causality between electricity consumption and long-term economic growth. Their study uses a panel data approach based on a sample of 160 countries classified as developed according to geographical location and income. They used data for the period 1980-2010 and accounted for the degree of electricity dependence and the level of urbanization.

Furthermore, in Pakistan, Shahbaz and Feridun (2012) found evidence for the feedback hypothesis after controlling for the major factors of production, capital, and labor. The authors use ARDL and VECM Granger causality techniques with data from 1972 to 2009. The study also accounts for electricity trade and urbanization in their model. Furthermore, Bayar and Özel (2014) documented the bidirectional causality between electricity consumption and economic growth in selected emerging economies using the VAR Granger causality technique and data covering the period 1970 to 2011. Furthermore, Gurgul and Lach (2012) documented evidence for the feedback theory between electricity consumption and economic growth in Poland. They used quarterly data from 2000 to 2009, employed the VECM approach, and controlled for employment. Similarly, Yoo and Kwak (2010) found a bidirectional causality between electricity consumption and economic growth in Venezuela using the Granger causality technique and data for 1975–2006. In addition, Ibrahiem (2022) investigate the causal relationship between electricity consumption and real output in Egypt, using data from 1971 to 2013. They used the Johansen cointegration approach, vector error correction model, and Toda and Yamamoto causality test and found empirical evidence for a bidirectional causality between real output and electricity consumption at the macro level. These studies suggest that these countries should explore and exploit new sources of electricity to achieve sustainable economic growth in the long run.

Regarding the conservation hypothesis of electricity consumption, the results of the study by Shahbaz and Feridun (2012) showed a positive unidirectional relationship between economic growth and electricity consumption in Pakistan. This study used the ARDL method with data from 1971-2008. Similarly, Karanfil and Li (2015) found support for the conservation hypothesis in the short term in the Middle East, Pacific, East Asia, North Africa and lower middle income subsamples. This implies that in the short run economic growth leads to increased electricity consumption; hence, energy conservation policies will not harm economic growth in the short run. In addition, Balcilar, Bekun, and Uzuner (2019) revisited the interaction between electricity consumption, real gross domestic product, and carbon dioxide emissions in Pakistan using annual data from 1971 to 2014, employing the Maki cointegration test and the Toda-Yamamoto causality test. They found evidence for the conservation hypothesis in Pakistan, implying that conservation energy strategies cannot harm economic growth.

Considering the neutrality hypothesis, Karanfil and Li (2015) found evidence for this hypothesis in their empirical panel data study. The researchers found no relationship between electricity consumption and economic growth in the short run in their North America, Sub-Saharan Africa, and Upper Middle Income Country sub-samples. Likewise, Yoo and Kwak (2010) found no relationship between electricity consumption and economic growth in Peru using the Granger causality technique for a period from 1975 to 2006. Also, Menegaki and Tugcu (2016) examined the energy-growth nexus using data from 42 Sub-Saharan African (SSA) countries from 1985 to 2013 while controlling for capital, CO2 emissions, rents, trade and inflation. They used the panel data cointegration approach and the Granger causality test. Using GDP as the measure of income, they demonstrated the neutrality hypothesis in Sub-Saharan Africa.

Table 1 summarizes the above studies and illustrates well the contradictory findings in the literature. The results vary according to country contexts, study period, and data. The findings also vary regardless of the econometric methods used. Using the same econometric method for a different data set does not guarantee a similar conclusion on the electricity consumption-economic growth nexus. Therefore, the difference in results is limited not only to differences in the country context but also in the control variables included in the model, the study period, and the data.

Specifically for Uganda, the research literature on the electricity consumption-economic growth nexus is limited. Studies in this area find somewhat contradictory results. In the long run, Sekantsi and Okot (2016) found a bidirectional causality between electricity consumption and economic growth in Uganda. The study used annual data from 1982 to 2013, the ARDL technique, and Granger causality tests. Mutumba et al. (2022) using quarterly data for the period 2008Q1–2018Q4 and including variables for gross capital formation and population in the model, find support for a bidirectional Granger causality using a VECM model.

Table 1. Summary of recent relevant literature on electricity consumption and economic growth.

Authors	Control variables	Research method	Findings	Period	Context
Yoo and Kwak (2010)		Granger causality	Growth	1975–2006	Argentina, Brazil, Chile, Columbia, Ecuador
Iyke (2015)	Inflation	VECM	Growth	1971–2011	Nigeria
Mawejje and Mawejje (2016)		VECM	Growth	2005–2015	Uganda
Samu, Bekun, and Fahrioglu (2019)	CO_2 emissions	Maki cointegration and the Toda-Yamamoto causality	Growth	1971–2014	Zimbabwe
Lawal et al. (2020)	Financial development, foreign direct investment, trade, government spending, life expectancy, education, inflation, labor, savings rate, governance effectiveness	System GMM	Growth	1971–2017	17 sub-Saharan countries
Churchill and Ivanovski (2020)	Labor and capital	Panel data	Growth	1990–2015	Australia
Alinda et al. (2022)	Gross fixed capital formation	VECM	Growh	1986–2017	Uganda
Yoo and Kwak (2010)		ARDL	Feedback	1975–2006	Venezuela
Gurgul and Lach (2012)	Employment	VECM	Feedback	2000–2009	Poland
Shahbaz and Lean (2012)	Capital, labor, electricity trade, urbanization	ARDL, VECM	Feedback	1972–2009	Pakistan
Ogundipe and Apata (2013)	Capital and labor	VECM	Feedback	1980–2008	Nigeria
Polemis and Dagoumas (2013)	Employment, electricity price	VECM	Feedback	1970–2011	Greece
Bayar and Özel (2014)		VAR	Feedback	1970–2011	Brazil, Chile, China, Colombia, Czech Republic, Egypt, Greece, Hungary, India, Indonesia, Korea, Malaysia, Mexico, Peru, Philippines, Poland, Russia, South Africa, Taiwan, Thailand, Turkey
Kasperowicz (2014)	Capital, employment	Granger causality	Feedback	2000–2012	Poland
Hamdi, Sbia, and Shahbaz (2014)	Capital, foreign direct investment	ARDL, Granger causality	Feedback	1980–2010	Bahrain
Karanfil and Li (2015)	Degree of electricity dependency, urbanization	Panel data	Feedback	1980–2010	160 countries
Osman, Gachino, and Hoque (2016)	Gross fixed capital formation	Panel VAR	Feedback	1975–2012	GCC countries
Sekantsi and Okot (2016)		ARDL	Feedback	1982–2013	Uganda
Ibrahiem (2022)			Feedback	1971–2013	Egypt
Mutumba et al. (2022)	Gross fixed capital formation	VECM	Feedback	2008–2018	Uganda
Shahbaz and Feridun (2012)		ARDL	Conservation	1971–2008	Pakistan
Karanfil and Li (2015)	Degree of electricity dependency, urbanization	VECM	Conservation	1980–2010	Middle East, Pacific, East Asia, North Africa, Lower-Middle Income Countries
Balcilar, Bekun, and Uzuner (2019)	CO_2 emissions	Maki cointegration and Toda-Yamamoto causality	Conservation	1971–2014	Pakistan
Yoo and Kwak (2010)		Granger casulity	Neutrality	1975–2006	Peru
Karanfil and Li (2015)	Degree of electricity dependency, urbanization	VECM	Neutrality	1980–2010	North America, sub-Saharan Africa, Upper-Middle Income countries
Menegaki and Tugcu (2016)	CO_2 emissions	Panel data cointegration and Granger causality	Neutrality	1985–2013	sub-Saharan Africa

These results are in agreement with the feedback hypothesis.

However, Mawejje and Mawejje (2016) documented evidence of the growth hypothesis in Uganda, indicating a unidirectional causality from electricity consumption to economic growth. They used the VECM approach and quarterly data from 2005 to 2015. Furthermore, Alinda et al. (2022), using annual data for the period 1986–2017, and including gross fixed capital formation in their model, find a unidirectional causality from electricity expenditures (as an expression for consumption) to GDP.

Differences in the results of these studies may be due to the fact that Mawejje and Mawejje (2016) do not include investment as an explanatory variable. Investment measured as gross fixed capital formation is a statistically significant explanatory variable in regression models with GDP as the dependent variable (Sekantsi and Okot 2016; Alinda et al. 2022; Mutumba et al. 2022). However, this variable is troublesome for at least two reasons. First, gross fixed capital formation covers both the depreciation of the capital stock and the net change in the capital stock. Second, the neoclassical model growth model, which serves as the conceptual basis for these studies, relates the output produced measured as GDP to capital stock, labor and a number of other variables (Barro and Sala-i-Martin 2003). The use of gross fixed capital formation as a proxy for capital stock may introduce measurement errors in the empirical models and influence the empirical results. The next section presents the neoclassical growth model and describes the perpetual inventory model as a means to construct the unobserved capital stock variable from the observed gross fixed capital formation variable.

3. Methods and Data

3.1. *Growth model*

The starting point for much of the analysis of economic growth and electricity (energy) usage is the neoclassical economic growth model, or variants thereof (Barro and Sala-i-Martin 2003). Consider the aggregate production function:

$$Y_t = f(K_t, L_t, E_t, t) \tag{1}$$

where Y_t is aggregate output, K_t is the capital stock, L_t is the labor force, and E_t is the energy use at time t. The production function is often specified as a Cobb-Douglas production function with a Hicks neutral technical change rate γ. In log-form the production function is

$$\ln Y_t = \alpha_0 + \beta_K \ln K_t + \beta_L \ln L_t + \beta_E \ln E_t + \gamma_0 t. \tag{2}$$

Accurate and current data on population and labor force are notoriously hard to obtain for many countries, and Uganda is no exception. Population data are collected only through censuses every 10 to 12 years, the last of which took place in 2014. However, the International Labor Organization provides estimates and forecasts for total employment in most countries, including Uganda. As can be seen in Figure 2, the labor force has been increasing rather steadily without any clear cyclical patterns. Thus, rather than using model-based data for the size of the labor force, we could include the growing labor force in the time trend.

Assume that the labor force is growing at a periodic rate of γ_L. The labor force at time t is

$$L_t = L_0 e^{\gamma_L t}$$

where L_0 is the initial size of the labor force. The growth in the labor force acts as Harrod neutral technical change, and with the Cobb-Douglas production specification, will be absorbed into the Hicks technical change parameter. The production function becomes

$$\ln Y_t = \alpha + \beta_K \ln K_t + \beta_E \ln E_t + \gamma t \tag{3}$$

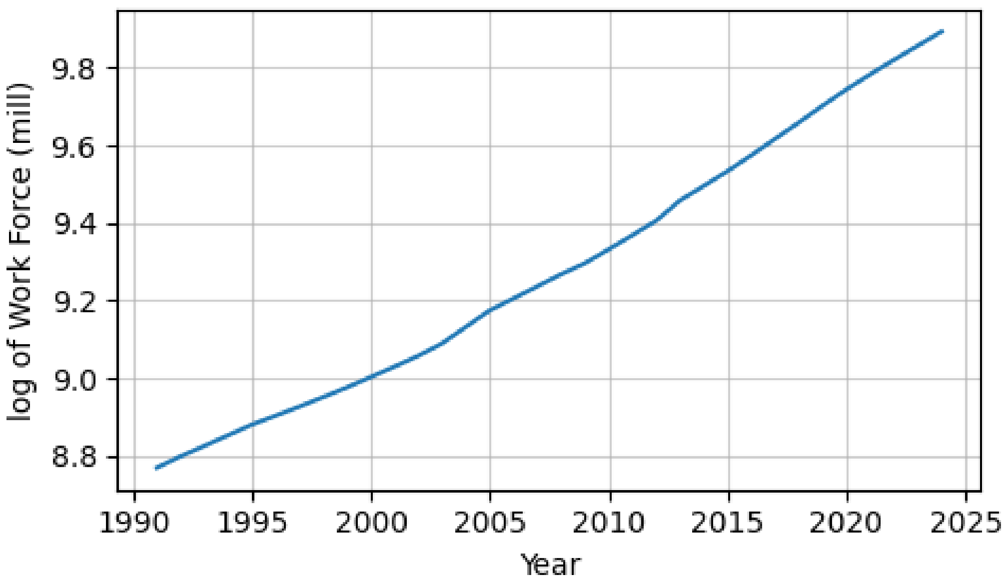
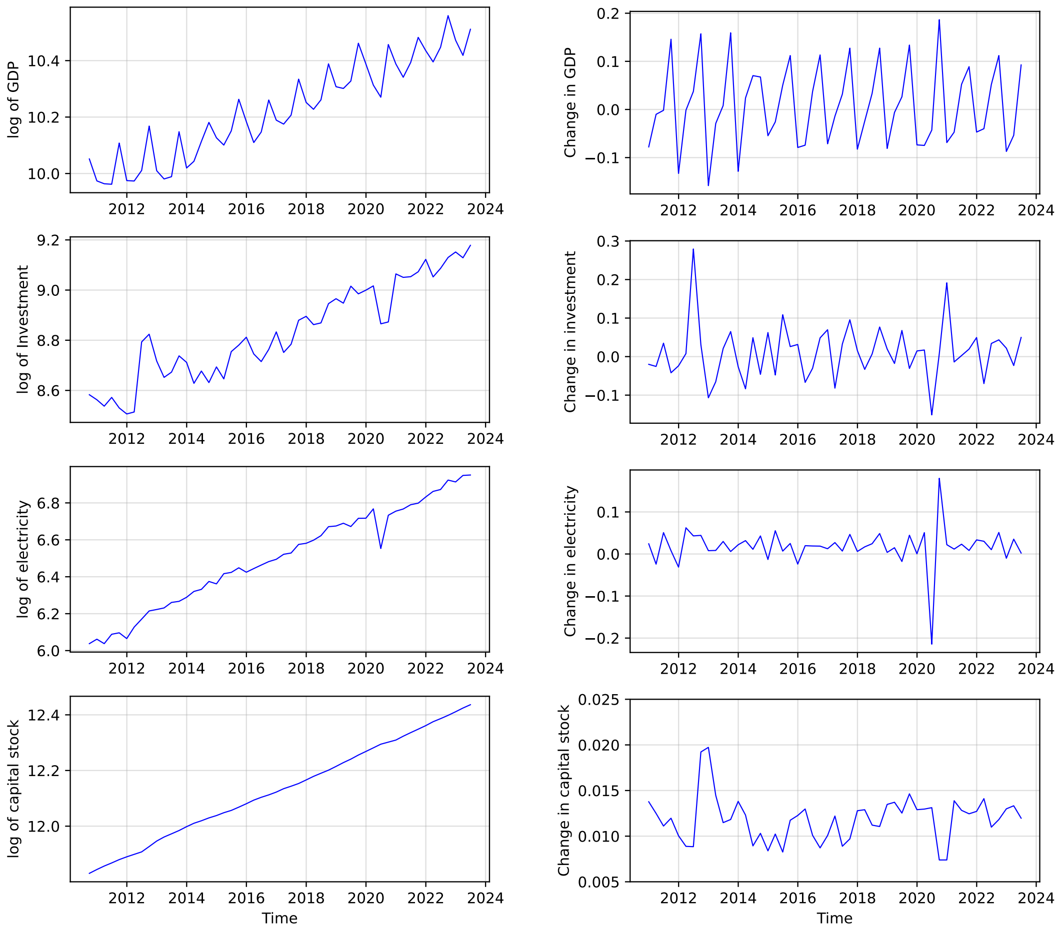


Figure 2. Estimate and forecast of labor force in Uganda. Source: International Labor Organization.

where the initial labor force is included in the constant term and the time trend accounts for both technical change and growth in the labor force. The models in equations (2) and (3) will be the basis for our empirical analysis.

3.2. *Data sources*

Macroeconomic data for Uganda are available from the Uganda Bureau of Statistics (UBOS). We are using quarterly series for the gross domestic product (GDP) and gross capital formation (GCF) measured in billions of Ugandan shillings (UGX) at constant 2016/2017 prices. The series covers the period 2010Q3—-2023Q2 and are not seasonally adjusted. There are earlier quarterly GDP data from UBOS that have been reported in current prices. However, the latest price deflator used by UBOS extends back in time to 2010Q3. Deflating price series with data before and after this date would require the use of two different price deflators. As the two price deflators differ noticeably, the use of two deflators would introduce measurement errors in the data. Quarterly electricity consumption (ELC) data for the same period were obtained from the Electricity Regulatory Authority and are measured in GWh.



(a) Logarithmic values.

(b) First difference of values.

Figure 3. Logarithmic values and change in logarithmic values of gross domestic product (GDP), investment (gross fixed capital formation), electricity consumption and fixed capital stock.

UBOS also provides a quarterly series for GDP that has been seasonally adjusted. However, neither the time series for gross capital formation nor the electricity consumption is available as seasonally adjusted series. We are using only the unadjusted series in order to maintain consistency between the different series. As noted in Bell and Hillmer (1984) and Enders (2014), seasonal adjustment of time series changes the statistical properties of the time series. Thus, we explicitly take care of any seasonality in our testing and estimation procedures.

Table 3. Summary statistics. Sample period 2010Q3 to 2023Q2. $n = 52$.

Variable	Mean	Std dev	Minimum	Maximum
Gross domestic product	27994	21203	38540	4803
Gross fixed capital formation	6985	4945	9686	1342
Electricity consumption	692	419	1044	183

3.3. *Summary statistics*

Summary statistics are reported in Table 3. Figure 1 gives a graphical representation of the trends in GDP and electricity consumption in Uganda. The seasonal pattern in GDP is clearly visible, but not for the other series. The lockdown associated with the Covid-19 pandemic coincides with a lower investment level in 2020Q2, as well as a transitory reduction in electricity consumption in the same period.

3.4. *Capital stock*

Data about physical capital stock are not available from UBOS. We used the perpetual inventory model (Griliches 1980; Jacob, Sharma, and Grabowski 1997) to construct a quarterly series for capital stock. Following the approach of Berlemann and Wesselhöft (2014), the initial capital stock is

$$K_0 = \frac{I_0}{\delta + \gamma} \tag{4}$$

where δ is the capital depreciation rate, γ is the long-term growth rate of the investment and I_0 is the initial investment. Using the observed data on capital formation, I_t, in the time period (quarter) $t = 0, 1, \ldots, T-1$, we estimate the following equation using OLS:

$$\ln I_t = \alpha + \gamma t + \varepsilon_t.$$

This gives an estimate of the long-term growth rate of investments, $\hat{\gamma} = 0.0119$, and the intercept, $\hat{\alpha} = 8.3505$, is an estimate of the initial investment (I_0) in equation (4). The estimated growth rate in investment is approximately 4. 8% annually. The depreciation rate δ is set at 0.025 (that is, 10% annually), which is consistent with other studies (Griliches 1980; Bu 2006; Berlemann and Wesselhöft 2014)[2]. Given the estimate of the initial capital stock from equation (4), the quarterly values of the capital stock are calculated from the actual investments I_t as

$$K_{t+1} = (1 - \delta)K_t + I_t. \tag{5}$$

The constructed time series for capital is shown in Figure 3 along with the observed variables.

3.5. *Unit root tests*

The time series from UBOS that we are using are not adjusted for seasonality. This can be clearly seen in Figure 3 for GDP. However, the other series do not show a clear seasonal pattern. We tested the stationarity of the GDP, capital, and electricity consumption series using Augmented Dickey-Fuller (ADF) tests with drift (Hansen 2022). Furthermore, the regression model used in the ADF test is extended with centered quarterly dummy variables (Enders 2014). The ADF t-values are reported in Table 4 along with the lag length determined by minimizing Akaike's Information Criteria (AIC). The critical value for the ADF test with drift is -2.92 at the 5% level. Thus, we conclude that these three time series are nonstationary.

The potential seasonality in the first difference of the data is removed by taking the differnce between observations four quarters apart, i.e., the year-on-year change. The results of the ADF test on the seasonally differenced data are reported in Table 4. The critical value for the ADF test is -1.95 at the 5% level. The

[2]Changing the depreciation rate changes the empirical results marginally, and does not change the qualitative conclusions.

Table 4. Augmented Dickey-Fuller (ADF) tests for unit root with drift of log of real values and adjusted for seasonality. Lag length selection based on minimizing Akaike's Information Criteria (AIC). Sample period 2010Q3 to 2023Q2.

	Level		First difference	
Variable	Lags	ADF	Lags	ADF
$\ln Y$	1	0.066	0	-4.367
$\ln K$	2	0.169	1	-4.193
$\ln E$	2	-0.639	0	-5.787

differenced data series are stationary, and we conclude that all three time series are integrated of order one.

3.6. *Testing for cointegration*

The tests in the previous section find that the variables are all non-stationary. The production function in equation (3) suggests that output could be a logarithmic linear function of capital, electricity consumption and a trend. The literature on the growth-energy nexus finds in most studies that GDP and energy (electricity) consumption are cointegrated. We will test co-integration using the Engle-Granger test (Engle and Granger 1987; Hansen 2022). An advantage of using the Engle-Granger test is that inclusion of centered quarterly dummy variables controls for seasonality (Enders 2014). The estimation results using OLS are shown in Table 5. The estimated coefficient for the capital stock at -1.59 has clearly the wrong sign and magnitude for a production function of the Cobb-Douglas type. The capital stock is increasing smoothly for the entire time period, as can be seen in Figure 3. With a time trend in the regression model, the estimated coefficient for the capital variable can reflect deviations from the trend and not represent the contribution of capital in the production process. Table 6 reports the OLS estimates for a model specification without the trend variable.

The Engle-Granger test for cointegration is an ADF test for the stationarity of the residuals from the regression model. The ADF t-value with one lag is -3.05 for the regression model with trend, and -2.80 for the model without trend included.

Table 5. OLS estimates of the aggregate production function including trend and quarter dummy variables. Sample period 2010Q3 to 2023Q2. $N = 52$.

Variable	Estimated coefficient	Standard error	t-value	p-value
Intercept	27.351	7.595	3.601	0.001
ln K	-1.594	0.640	-2.489	0.017
ln E	0.241	0.096	2.499	0.016
Trend	0.025	0.008	3.287	0.002
Quarter 1	-0.040	0.010	-4.147	0.000
Quarter 2	-0.014	0.010	-1.414	0.164
Quarter 3	0.094	0.010	9.666	0.000

Table 6. OLS estimates of the aggregate production function including quarter dummy variables. Sample period 2010Q3 to 2023Q2. $N = 52$.

Variable	Estimated coefficient	Standard error	t-value	p-value
Intercept	2.677	1.262	2.121	0.039
ln K	0.457	0.159	2.876	0.006
ln E	0.308	0.104	2.968	0.005
Quarter 1	-0.043	0.011	-4.017	0.000
Quarter 2	-0.013	0.011	-1.239	0.222
Quarter 3	0.095	0.011	8.817	0.000

The critical value for the Engle-Granger test with three time series and a trend is -4.12 at the conventional 5% level (Hansen 2022). The critical value without a trend is -3.74. Thus, we reject the hypothesis that the variables are cointegrated.

3.7. ***VAR model and Granger causality***

The lack of cointegration between GDP, capital stock, and electricity consumption rules out the use of error correction models, and the vector autoregressive model (VAR) is appropriate (Menegaki 2019; Hansen 2022). The VAR model in seasonal first differences with p lags for GDP, capital stock, and electricity consumption is given in equations (6), (7), and (8), respectively. The difference symbol Δ_4 is used to denote that the difference refers to the quarter of the year before.

$$\Delta_4 \ln Y_t = \alpha^Y + \sum_{i=1}^{p} \beta_i^Y \Delta_4 \ln Y_{t-i} + \sum_{i=1}^{p} \theta_i^Y \Delta_4 \ln K_{t-i} + \sum_{i=1}^{p} \psi_i^Y \Delta_4 \ln E_{t-i} + \varepsilon_t^Y \quad (6)$$

$$\Delta_4 \ln K_t = \alpha^K + \sum_{i=1}^{p} \beta_i^K \Delta_4 \ln Y_{t-i} + \sum_{i=1}^{p} \theta_i^K \Delta_4 \ln K_{t-i} + \sum_{i=1}^{p} \psi_i^K \Delta_4 \ln E_{t-i} + \varepsilon_t^K \quad (7)$$

$$\Delta_4 \ln E_t = \alpha^E + \sum_{i=1}^{p} \beta_i^E \Delta_4 \ln Y_{t-i} + \sum_{i=1}^{p} \theta_i^E \Delta_4 \ln K_{t-i} + \sum_{i=1}^{p} \psi_i^E \Delta_4 \ln E_{t-i} + \varepsilon_t^E. \quad (8)$$

Selection of the lag length p in the VAR model is usually based on minimizing an information criteria such as Akaike's Information Criteria (AIC), Bayesian Information Criteria (BIC) or Hannan-Quinn Information Criterion (HQC) (Enders 2014). The BIC and HQC are often preferred as these criteria have desirable large sample properties, while the AIC tends to favor models with too many variables. However, in small samples, the BIC and HQC tend to select models with too few variables.

The hypothesis that electricity consumption Granger causes economic growth (that is, a change in GDP) is a test for $\psi_i^Y = 0, i = 1, \ldots, p$ in equation (6). The reverse test for Granger causality from economic growth to electricity consumption is a test for $\beta_i^E = 0, i = 1, \ldots, p$ in equation (8).

4. Results

All models include a centered dummy variable for 2020Q2 associated with the Covid-19 lockdown period that slowed economic activity in general, and investment and electricity consumption, especially, as is evident from the graphs in Figure 3.

The information criteria are calculated for the VAR model with lag lengths $p = 1, \ldots, 6$, and the values are reported in Table 7. The BIC selects $p = 1$, the HQC selects $p = 2$, and the AIC selects $p = 6$ which is the largest value considered. Thus, the three information criteria do not agree on the best lag length for the VAR model. The results of testing for serial correlation in the residuals for

Table 7. Calculated value of Akaike's information criteria (AIC), Bayesian information criteria (BIC), and Hanna-Quinn information criteria (HQC) for different lag lengths in the VAR model. Sample period 2030Q1 to 2023Q2. N = 42.

Lag length	AIC	BIC	HQC
1	-700.61	-674.55	-691.06
2	-713.75	-672.05	-698.46
3	-718.22	-660.88	-697.20
4	-723.10	-650.11	-696.35
5	-720.17	-631.54	-687.68
6	-725.55	-621.29	-687.33

the VAR(1) model using a Lagrange Multiplier test show that there is a statistically significant AR(2) model for the residuals ($p = 0.032$). The VAR(2) model has a significant AR(1) model for the residuals ($p = 0.027$). In the VAR(3) model the AR(1) model for the residuals is not statistically significant ($p = 0.445$), nor are any higher-order AR models. Thus, the VAR model with three lags is dynamically complete, and we will use this model for the Granger causality tests. The estimated VAR model with three lags ($p = 3$) is reported in Table 8.

The results of the Granger causality test in the VAR model are reported in Table 9. The reported χ^2 values with three degrees of freedom imply p values higher than the common critical level of 5% (or 10%). Thus, we fail to reject both null hypothesis and conclude that there is no Granger causality from electricity consumption to economic growth, or vice versa.

5. Discussion

Our empirical analysis using quarterly data from 2010Q3 to 2023Q2 supports the neutrality hypothesis. This result is contrary to the results of previous studies on the energy-growth nexus in Uganda. Mawejje and Mawejje (2016) found support for the growth hypothesis using quarterly data. Sekantsi and Okot (2016) and Alinda et al. (2022) found support for the bidirectional hypothesis using annual data, while Mutumba et al. (2022) also found support for the bidirectional hypothesis using quarterly data.

Table 8. Estimated VAR model with lag $p = 3$. Sample period 2010Q3 to 2023Q2. $N = 44$.

		$\Delta_4 \ln Y$			$\Delta_4 \ln K$			$\Delta_4 \ln E$		
Variable	Lag	Estimated coefficient	Standard error	p-value	Estimated coefficient	Standard error	p-value	Estimated coefficient	Standard error	p-value
$\Delta_4 \ln Y$	1	0.2637	0.1409	0.061	0.0218	0.0110	0.047	0.2605	0.1822	0.153
	2	-0.0002	0.1573	0.999	-0.0213	0.0123	0.082	-0.3349	0.2034	0.100
	3	0.0892	0.1582	0.573	-0.0091	0.0123	0.462	-0.1539	0.2046	0.452
$\Delta_4 \ln K$	1	0.7504	1.7888	0.675	1.4164	0.1394	0.000	2.4623	2.3132	0.287
	2	-7.3285	2.6622	0.000	-0.6184	0.2075	0.003	-6.4489	3.4429	0.061
	3	6.6065	1.7069	0.000	-0.0232	0.1330	0.862	3.2076	2.2074	0.146
$\Delta_4 \ln E$	1	0.0001	0.1058	1.000	0.0173	0.0082	0.036	0.0126	0.1369	0.927
	2	-0.0176	0.1061	0.522	0.0165	0.0083	0.046	0.2531	0.1372	0.086
	3	0.1142	0.1150	0.357	-0.0127	0.0090	0.156	0.2124	0.1487	0.153
Covid		-0.0959	0.0296	0.001	0.0042	0.0023	0.066	-0.1529	0.0383	0.000
Intercept		0.0147	0.0455	0.746	0.0095	0.0035	0.007	0.0875	0.0588	0.136

Table 9. Pairwise test Granger causality tests.

Hypothesis	Null hypothesis	χ^2-value	p-value
Electricity consumption Granger causes GDP	$\psi_i^Y = 0, i = 1, 2, 3$	1.206	0.751
GDP Granger causes electricity consumption	$\beta_i^E = 0, i = 1, 2, 3$	4.822	0.185

All of these studies use data in their analysis from the high growth period before 2011 and the slow growth period after 2011. Neither of the studies test for a structural break. If there has been a structural break in the Ugandan economy this could explain why our conclusions are different from the previous studies. The existence of such a structural break would imply that the conclusions of previous studies may no longer hold, something that has implications for policy recommendations.

The neoclassical growth model underpinning much of the research on the economic growth-energy use nexus is based on an aggregate production model with labor, fixed capital stock, energy, and other inputs. Alinda et al. (2022) and Mutumba et al. (2022) use gross fixed capital formation as a proxy for fixed capital in their empirical models. In contrast, we construct a capital stock variable from information about investments (gross capital formation) using well-established methods (Berlemann and Wesselhöft 2014). Thus, our model estimates are based on variables which are closer to the theoretical model, avoiding the need for a proxy variable.

6. Conclusions

In this study, we examine the relationships between economic growth and electricity consumption while controlling for capital stock, one of the major determinants of economic growth, using quarterly data from Uganda from 2010Q3 to 2023Q2. Using the Engle-Granger cointegration test, we find no evidence of cointegration between GDP, capital stock, and electricity consumption. A Granger causality test based on a VAR (3) model finds no empirical evidence of a relationship between economic growth and electricity consumption. Therefore, our analysis lend support for the neutrality hypothesis.

Our results are similar to Menegaki and Tugcu (2016), Karanfil and Li (2015), and Yoo and Kwak (2010), among others, who found support for the neutrality hypothesis that there is no causality between economic growth and electricity consumption. However, our results differ from the previous analysis by Mawejje and Mawejje (2016) who found support for the growth hypothesis, and Sekantsi and Okot (2016), Alinda et al. (2022), and Mutumba et al. (2022) who found support for the feedback hypothesis.

One possible reason for the divergence in the results may be differences in the time period used in the empirical analysis. Our analysis is based on data from 2011 onward. The Ugandan economy was growing rapidly until about 2011 and then settled at a slower growth rate. Previous studies used data from both periods without testing or controlling for a possible structural break in the growth pattern.

The existence of a possible structural break in the growth pattern warrants further study. The study of factors that influence economic growth in Uganda by Sendi, Mayanja, and Nyorekwa (2021) should be re-visited with updated and enhanced data to determine whether there has indeed been a structural break in the growth pattern in Uganda. Also, our analysis could be extended to earlier periods, if data is available, to ascertain if there has been a structural break.

Author Contributions: Conceptualization, G.A.; methodology, G.A.; formal analysis, G.A. and O.B.; data curation, G.A. and O.B.; writing—original draft preparation, G.A.; writing—review and editing, G.A. and O.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the Norwegian Programme for Capacity-Building in Higher Education and Research for Development (NORHED), project number: QZA-0486-13/0017.

Data Availability Statement: The data used in this study is available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

Alinda, K., S. Tumwine, T. Kaawaase, S. Navrud, I. Nalukenge, and A. Sserwanga. 2022. "Evidence of Causality between Economic Growth and Electricity Consumption Expenditure in Uganda." *Journal of Energy Research and Reviews* 10 (2): 1–18.

Balcilar, M., F. V. Bekun, and G. Uzuner. 2019. "Revisiting the economic growth and electricity consumption nexus in Pakistan." *Environmental Science and Pollution Research* 26 (12): 12158–12170.

Barro, R. J., and X. Sala-i-Martin. 2003. *Economic Growth*. Cambridge, MA: The MIT Press.

Bayar, Y., and H. A. Özel. 2014. "Electricity Consumption and Economic Growth in Emerging Economies." *Journal of Knowledge Management, Economics and Information Technology* 4 (2): 1–18.

Bell, W. R., and S. C. Hillmer. 1984. "Issues Involved With the Seasonal Adjustment of Economic Time Series." *Journal of Business & Economic Statistics* 2 (4): 291–320.

Berlemann, M., and J.-E. Wesselhöft. 2014. "Estimating Aggregate Capital Stocks Using the Perpetual Inventory Method." *Review of Economics* 65 (1): 1–34.

Bu, Y. 2006. "Fixed capital stock depreciation in developing countries: Some evidence from firm level data." *The Journal of Development Studies* 42 (5): 881–901.

Churchill, S. A., and K. Ivanovski. 2020. "Electricity consumption and economic growth across Australian states and territories." *Applied Economics* 52 (8): 866–878.

Enders, W. 2014. *Applied Econometric Time Series*. Wiley series in probability and statistics. Wiley.

Engle, R. F., and C. W. J. Granger. 1987. "Co-Integration and Error Correction: Representation, Estimation, and Testing." *Econometrica* 55 (2): 251–276.

Griliches, Z. 1980. "R & D and the Productivity Slowdown." *The American Economic Review* 70 (2): 343–348.

Gurgul, H., and Ł. Lach. 2012. "The electricity consumption versus economic growth of the Polish economy." *Energy Economics* 34 (2): 500–510.

Hamdi, H., R. Sbia, and M. Shahbaz. 2014. "The nexus between electricity consumption and economic growth in Bahrain." *Economic Modelling* 38: 227–237.

Hansen, B. E. 2022. *Econometrics*. Princeton, NJ: Princeton University Press.

Ibrahiem, D. M. 2022. "Investigating the causal relationship between electricity consumption and sectoral outputs: evidence from Egypt." *Energy Transition* 2 (1): 31–48.

IEA. 2023. *Uganda 2023*. Energy policy review. Paris: International Energy Agency. https://www.iea.org/reports/uganda-2023.

Iyke, B. N. 2015. "Electricity consumption and economic growth in Nigeria: A revisit of the energy-growth debate." *Energy Economics* 51: 166–176.

Jacob, V., S. C. Sharma, and R. Grabowski. 1997. "Capital stock estimates for major sectors and disaggregated manufacturing in selected OECD countries." *Applied Economics* 29 (5): 563–579.

Karanfil, F., and Y. Li. 2015. "Electricity consumption and economic growth: Exploring panel-specific differences." *Energy Policy* 82: 264–277.

Kasperowicz, R. 2014. "Electricity consumption and economic growth: evidence from Poland." *Journal of International Studies* 4: 46–57.

Kraft, J., and A. Kraft. 1978. "On the Relationship Between Energy and GNP." *The Journal of Energy and Development* 3 (2): 401–403.

Lawal, A. I., I. Ozturk, I. O. Olanipekun, and A. J. Asaleye. 2020. "Examining the linkages between electricity consumption and economic growth in African economies." *Energy* 208: 118363.

Mawejje, J., and D. N. Mawejje. 2016. "Electricity consumption and sectoral output in Uganda: an empirical investigation." *Journal of Economic Structures* 5.

Menegaki, A. N. 2019. "The ARDL Method in the Energy-Growth Nexus Field; Best Implementation Strategies." *Economies* 7 (4).

Menegaki, A. N., and C. T. Tugcu. 2016. "Rethinking the energy-growth nexus: Proposing an index of sustainable economic welfare for Sub-Saharan Africa." *Energy Research and Social Science* 17: 147–159.

Mutumba, G. S., T. Odongo, N. F. Okurut, and V. Bagire. 2021. "A survey of literature on energy consumption and economic growth." *Energy Reports* 7: 9150–9239.

Mutumba, G. S., J. Otim, S. Watundu, M. S. Adaramola, and T. Odongo. 2022. "Electricity consumption and economic growth in Uganda." In *Advances in Phytochemistry, Textile and Renewable Energy Research for Industrial Growth*, edited by C. Nzila, N. Oluoch, A. Kiprop, R. Ramkat, and I. Kosgey, 275–285. Boca Raton, USA: CRC Press.

Ogundipe, A. A., and A. Apata. 2013. "Electricity Consumption and Economic Growth in Nigeria." *Journal of Business Management and Applied Economics* 2 (4): 1–14.

Osman, M., G. Gachino, and A. Hoque. 2016. "Electricity consumption and economic growth in the GCC countries: Panel data analysis." *Energy Policy* 98: 318–327.

Ozturk, I. 2010. "A Literature Survey on Energy–Growth Nexus." *Energy Policy* 38 (1): 340–349.

Polemis, M. L., and A. S. Dagoumas. 2013. "The electricity consumption and economic growth nexus: Evidence from Greece." *Energy Policy* 62: 798–808.

Samu, R., F. V. Bekun, and M. Fahrioglu. 2019. "Electricity consumption and economic growth nexus in Zimbabwe revisited: fresh evidence from Maki cointegration." *International Journal of Green Energy* 16 (7): 540–550.

Sekantsi, L. P., and N. Okot. 2016. "Electricity consumption–economic growth nexus in Uganda." *Energy Sources, Part B: Economics, Planning, and Policy* 11 (12): 1144–1149.

Sendi, R., J. B. Mayanja, and E. Nyorekwa. 2021. "Determinants of Economic Growth: An Empirical Evaluation of the Ugandan Economy." In *Macroeconomic Analysis for Economic Growth*, edited by M. J. Ibrahim, Chap. 2. Rijeka: IntechOpen.

Shahbaz, M., and M. Feridun. 2012. "Electricity consumption and economic growth empirical evidence from Pakistan." *Quality & Quantity* 46: 1583–1599.

Shahbaz, M., and H. H. Lean. 2012. "The dynamics of electricity consumption and economic growth: A revisit study of their causality in Pakistan." *Energy* 39 (1): 146–153.

Yoo, S.-H., and S.-Y. Kwak. 2010. "Electricity consumption and economic growth in seven South American countries." *Energy Policy* 38 (1): 181–188.