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Energy poverty: Estimating the impact of solid cooking fuels on GDP per capita in developing countries - Case of sub-Saharan Africa

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ABSTRACT

Accessibility to modern energy services is imperative in resolving numerous present-day global development issues which affect people's socio-economic and physical well-being, plus, the potentiality of meeting the global goals of lessening carbon emissions. The absence of access, termed energy poverty in developing countries, has several key aspects: inaccessibility to electricity on demand, is one aspect. However, inaccessibility to modern (or clean) cooking fuels is another critical aspect. A cause and effect of households' continuous heavy reliance on traditional (or solid) fuels. Despite over a third of the global population having this issue, this aspect of energy poverty continues to be a severe, yet overlooked development issue: particularly in developing countries. A review of literature shows that there are currently no empirical studies which quantify the sole relationship between the utilization of traditional energy fuels for cooking and/or heating and economic development. Thus, in this paper, we advance existing literature in multiple-folds. Firstly, we provide a review in an absent area of literature. Secondly, using the data from 46 sub-Saharan African countries, we provide empirical evidence of the impacts of the continued utilization of traditional fuels on economic development (employing Gross Domestic Product (GDP) per Capita as variable). Following the establishment of a negative causal relationship running from traditional fuels use (solid) to GDP per capita, we provide an insight into policy implications. Finally, we comment on potential policy strategies.

o1. Introduction

In recent years, it has become extensively acknowledged that although accessibility to affordable modern energy by itself is not an elixir for all development problems in developing countries [1,2], it is crucial to economic, social and human development [3,4]. This absence, often labelled as energy poverty, impacts on people's health, productivity, and income [5,6]. More generally, energy poverty acts as a dominant obstacle in attaining development targets including the Sustainable Development Goals (SDGs) [7], and has become one of the key SDGs for 2030 (SDG 7).

In response to this, scientific and policy attention have focussed on matters of accessibility, equity and investment in social-technical systems linked to modern energy supply. However, most of this focus has been predominantly placed on electricity supply [8]. This is perhaps due to studies which have demonstrated the importance of electricity on aspects of sustainable development such as, improved productivity driving economic development [9], and improved lighting for day-to-day activities, driving social development [10,11].

Best and Burke [12]; Hirsh and Koomey [13]; and Chakamera and Alagidede [14] amongst several exemplary analyses have extensively evaluated the link between access and/or increased consumption of electricity and economic development, using GDP per Capita as instrument (see Table 2). The underlying theory of change presented by these studies has demonstrated that the provision of modern, clean electricity stimulates wider economic development which in turn stimulates households changing to cleaner energy supplies [15–17]. Across all of these studies, there is an assumption that the continued use of non-modern energy sources is detrimental to economic development as well as health (see Table 3).

Nevertheless, there remains a significant gap which continues to be overlooked by literature. Using data from the World Bank group,

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Table 1
Summary of empirical studies on energy consumption and economic development.

Author(s)	Countries	Variables	Methods	Conclusions
Ebohon (1996)	Nigeria, Tanzania	Energy consumption; GDP	Engle-Granger causality	EC ↔ GDP
Soytas and Sari (2003)	South-Africa	Energy consumption; GDP	Co-integration, causality	EC ← GDP
Wolde-Rufael (2005)	19 African countries	Energy consumption; GDP	ARDL bounds test; Toda and Yamamoto causality	EC → GDP (Cameroon, Morroco and Nigeria)
				EC ← GDP (Algeria, Congo DR, Egypt, Ghana and Ivory Coast)
				EC ↔ GDP (Gabon and Zambia)
				EC ⇼ GDP (Benin, Congo RP, Kenya, Senegal, South Africa, Sudan, Togo, Tunisia and Zimbabwe)
Akinlo (2008)	11 sub-Saharan countries	Energy consumption; GDP	ARDL bounds test	EC ⇼ GDP (Cameroon, Ivory Coast, Kenya, Nigeria and Togo)
Wolde-Rufael (2009)	Algeria, Benin and South Africa	Energy consumption; GDP	Toda and Yamamoto causality	EC ↔ GDP
Odhiambo (2009a)	Tanzania	Energy consumption; GDP	ARDL bounds test	EC → GDP
Odhiambo (2010)	Congo RD, Kenya and South Africa	Energy consumption; GDP	ARDL bounds test	EC → GDP (Kenya, South Africa)
				EC ← GDP (Congo RD)
Esso (2010)	7 African countries	Energy consumption; GDP	Threshold cointegration	EC ← GDP (Congo and Ghana)
				EC ↔ GDP (Ivory Coast)
				EC ⇼ GDP (Cameroon, Kenya, Nigeria and South Africa)

However, thus far, many studies have primarily focused on either the general energy - economic development connection or on the explicit connection between electricity and economic development [36].

Table 2
Summary of empirical studies on electricity consumption and economic development.

Author(s)	Countries	Variables	Methods	Conclusions
Abosedra	Lebanon	Electricity consumption; GDP	Granger causality	ELC → GDP
Akinlo (2007)	Nigeria	Electricity consumption; GDP	Johansen-Juselius; Cointegration; VEC; co-feature analysis	ELC → GDP
Jumbe (2004)	Malawi	Electricity consumption; GDP	Granger causality; ECM	EC ← GDP (Granger); ELC ↔ GDP (ECM)
Ouedrago (2010)	Burkina Faso	Electricity consumption; GDP	ARDL bounds test	ELC → GDP
Odhiambo (2009)	Tanzania	Electricity consumption; GDP	ARDL bounds test; cointegration; VEC	ELC → GDP
Odhiambo (2009)	South Africa	Electricity consumption; GDP	Johansen-Juselius; cointegration; VEC	ELC ↔ GDP
Wolde-Rufael (2006)	18 African countries	Electricity consumption; GDP	Todo-Yamamoto causality	ELC → GDP (Benin, Congo DR, Tunisia)
				ELC ← GDP (Cameroon, Gabon, Ghana, Nigeria, Senegal, Zambia and Zimbabwe)
				ELC ↔ GDP (Egypt, Morocco)
				ELC ⇼ GDP (Algeria, Congo RP, Kenya, South Africa and Sudan)

Table 3
Summary of empirical studies on biomass consumption and economic development.

Author(s)	Countries	Variables	Methods	Conclusions
Bildirici (2016)	8 African countries	Wood consumption (W); GDP	ARDL bounds test; Granger causality	W ↔ GDP (Benin, Mauritania, Nigeria and South Africa)
				W → GDP (Angola, Guinea-Bissau and Niger)
				W ← GDP (Seycelles)
Adewuyi (2017)	Some west African countries	Biomass (B); CO2 emission; GDP	Granger causality	B → GDP (Benin, Burkina-Faso, Gambia, Ghana, Mali, Nigeria and Senegal)
				B → GDP → CO2 (Burkina-Faso, Gambia, Mali, Nigeria and Togo)
Ozturk (2015)	Some sub-Saharan countries	Biomass (B); Openness (O); Population (P); GDP	OLS and DOLS; cointegration	B + O + P → GDP

across the world, while about 1.2 billion people still lack access to electricity, over 2.7 billion people still lack access to clean cooking fuels. For these population, the continued use of solid fuels for day-to-day activities such as cooking and/or heating is a necessity [18]. Studies such as Zulu and Richardson [19]; Hammond [20]; and Schlag [21] have established that previous assumptions that electricity could be used to address these needs, have been proven inaccurate [8,22]. Yet despite this, studies looking into the issue of clean energy for cooking and/or heating, as well as empirical studies investigating the link between the use of solid fuels for cooking and sustainable economic development are few and far between [23]. In fact, upon thorough review of literature, we find less than a handful of studies investigating the link between inaccessibility to clean energy for cooking and/or heating, and economic development.

Thereupon, this paper seeks to address this gap, through an exploration of the dimensions of the relationship between economic development and the use of solid fuels for cooking, in the context of sub-Saharan Africa. The sub-Saharan Africa region is considered in this paper because despite significant global growth in energy from clean and renewable sources, in recent years, sub-Saharan Africa has one of the highest concentrations of households which continue to use traditional sources of solid fuels for cooking and/or heating [24,25]. Thus, using data from sub-Saharan Africa, we explore this relationship asking two main questions:

- *Would enhanced economic development using GDP per Capita as variable, influence the nature of solid fuel trends?*
- *Or do solid fuel trends influence economic development?*

This paper uses the panel co-integration method to explore causality, and to consider the implications for energy policy. The principal contribution of our study is that it gives a perception of the significance of the continued use of solid fuels on economic development. From our results, we demonstrate the relationship hypotheses of solid fuel - GDP per Capita. Thus, giving an insight into appropriate policy approaches.

The remaining parts of this work discusses the existing empirical literature in section 2. Section 2.1 specifically depicts solid fuel use and economic activities in sub-Saharan Africa. The data and methodologies used in these analyses are discussed in section 3. Section 3.2 outlines the four stages associated with the panel co-integration approach, and summarise the basis for the subsequent analyses. Section 4 presents the results of these analyses, before turning to discuss wider significance, implications and conclusions in section 5.

2. Literature review

The pioneering study by Kraft and Kraft in 1978 [26] which demonstrated the presence of a unidirectional causal link between GNP and energy consumption, using data from the United States, provoked an extensive interest in the area of energy consumption-economic development nexus. Alone, the study by Ozturk [27] highlights that over sixty studies have investigated this link empirically. Indeed, the studies demonstrating the empirical link between energy and economic development hold important implications. Not only do these studies give important perceptions about the influence of energy on economic development, they also give a premise for the evaluation and design of policies relating to energy and environment. Yet, despite these policy implications, empirical studies on the link between energy consumption and economic development are yet to provide an unequivocal answer. Presently, there exists no unanimity on the nature of the link.

However, existing literature such as the study by Squalli, and the work by Ozturk [27], amongst others, have over the years indicated four potential relationship hypotheses and their policy implications: neutrality, conservation, growth and feedback.

- The neutrality hypothesis refers to cases where no causality link is observed between energy and economic development. Thus, implying that economic development and energy are not correlated. Consequently, for a country with such result, neither energy conservation nor energy expansion policies would influence the economy.
- In the conservation scenario, the causality is observed to run unidirectionally from economic development to energy. Therefore, policies which support the conservation of energy such as policies focusing on demand management, reduction of fossils fuels, amongst others, would not negatively impact on the economy of the country.
- On the other hand, the growth hypothesis denotes scenarios where the causality is observed to run from energy to economic development; meaning the economic development of the country is dependent on energy. This hypothesis implies that directly or indirectly, energy is a crucial determinant in a country's economic development.
- Finally, the feedback hypothesis refers to cases where there exists a bidirectional causal link between energy and economic development. Thus, implying energy and economic development are interconnected.

The work within this study adopts these hypotheses. The analyses will seek to establish the potential hypothesis relationship between the household use of solid fuels and economic development.

2.1. Energy-economic development nexus in sub-Saharan Africa

The significance of the inherent implications insinuated by the causal hypotheses have instigated the exploration of the causal relationship between energy and economic development by many scholars [28]. Recently, many of these works explore the causalilty between energy and economic development to encapsulate the fundamental impacts of several current energy issues on development [29,30]. This alongside how modern fuels contribute towards livelihood improvement and more extensively, human development [19], have become developing topics.

As regards sub-Saharan Africa, the energy issues experienced in the region's energy sector are becoming well documented and scholars are increasingly investigating the role energy plays in the development of the region. Starting in 1996, using the Granger causality method, Ebohon investigated the causal relationship between energy and economic development in two sub-Saharan countries: Tanzania and Nigeria [31]. More recently, using the Autoregressive Distribution Lag (ARDL) bounds as well as Granger causality method based on vector error correction model (VECM), Akinlo examined the causative link between energy and economic development across eleven sub-Saharan Africa countries [32]. Using the same approach, Odhiambo evaluated the link connecting energy and economic development in Tanzania [33]. The paper by Esso et al., that investigates the causal link between energy and economic development in five African nations [34]; Menegaki's study which looks into the energy-growth nexus for sub-Saharan Africa [35], are amongst recent works attempting to understand this relationship. These studies, along with several other studies which have investigated this causal linkages have observed varying conclusions. (See Table 1).

Recently, this relationship between access and/or increased electricity consumption and economic development has received significant academic and policy attention [37,38]. In 2017, using panel data across 174 countries, Atems and Hotaling [39], investigated the effects of renewable and non-renewable electricity generation on economic development. In their insightful study, Boukhelkhal and Bengana, using the ARDL approach, investigated the impact of electricity consumption on economic development, amongst other indicators, for four north African countries. Also using ARDL as well as the Toda and Yamamoto causality test, Bah and Azam examined the link between electricity consumption and economic development in South Africa [40]. In addition to other studies, these studies have examined the causal link between electricity and economic development, with varying and/sometimes contradicting outcomes.

2.2. Solid fuel and GDP in sub-Saharan Africa

In 2016, although the continent contributed to only 6% of the total global energy consumption, Africa contributed to almost 29% of the global biofuels consumption [41]. In the case of biofuels and biowaste, more than 50% of the overall energy consumption in the region was derived from these energy forms [42]. In sub-Saharan Africa, biofuels and biowaste contributed to over 70% of the total energy consumed within the region. Considering only solid biomass, approximately 280 million tonnes of oil equivalent (Mtoe) was consumed in the region - 90% of which was consumed by households. What's more, over 80% of the overall energy consumed within households was used for cooking [28].

As previously stated in section 1, despite significant global growth in energy from clean and renewable sources, in recent years, sub-Saharan Africa has one of the highest concentrations of households which continue to use traditional sources of solid fuels for cooking and/or heating [24,25]. In sub-Saharan Africa, the reality remains that over 792 million people depend on traditional fuels such as animal dung, coal, wood, for day-to-day cooking and heating activities [28]. In 2016/17, according to the World Bank, the aggregate access rates for electricity and clean cooking fuels in sub-Saharan Africa were estimated at approximately 35 % and 20% respectively. Over the last two decades, access to clean cooking fuels increased with an annual rate of less than 1% on average.

Yet, although literature acknowledges that many more people across the region lack access to clean cooking fuels than to electricity, much less attention has been given to the resolution of the issue [43].

Studies investigating the link between household use of solid fuels and economic development are limited, and far fewer studies have analysed the impact of household use of solid fuels on economic development. In the recent study by Adewuyi and Awodumi [44], the authors stress that only the study by Ozturk and Bilgili [45] has considered this relationship in the context of sub-Saharan Africa. What's more, these studies are mostly based off of time-series data of individual countries. To our knowledge, there exists no studies which utilise panel unit root and co-integration methods to analyse the solid fuel-economic development relationship. In addition, to the best of our knowledge, there are currently no studies investigating the link between household use of solid fuels and economic development. Thus, this paper makes a contribution to existing literature through investigating the causality between the household use of solid fuels and economic development for forty-six sub-Saharan countries, using the Fully Modified OLS (FMOLS) by Pedroni [46] and Dynamic Ordinary Least Square (DOLS) by Kao [47] methods. We also use panel Vector Error Correction Model (VECM) to check for robustness of the empirical results.

3. Data and methodology

Data measuring households utilizing solid fuels as the primary energy sources have been collected primarily through household surveys [48] but have been augmented by estimates for the purposes of the observation of trends and the provision of point estimates for countries and regions in explicit years [41]. Whilst previously there were few national representative surveys, making trend analysis problematic [49], in recent years, increased numbers of national surveys and additional surveys by WHO have expanded available data points [50]. In this analysis, we draw upon this recent data to examine relationships between the household use of solid fuels (hereafter 'solid') and Gross Domestic Product per Capita (hereafter 'GDP') using panel cointegration methods [30,51]. This approach enables relationships between variables to be revealed while allowing for heterogeneity among individual members of the panel.

3.1. Data

As previously stated, the analyses performed in this paper are based on data collated by the World Bank Group, for the 46 sub-Saharan Africa countries [41]. The variables used are based on the annual time series on access to clean cooking fuel and annual time series on Gross Domestic Product (GDP) per capita for these countries, over a period of 15 years. As noted above, data on access to clean cooking fuels has been collected through national surveys and collated into a regional WHO Global Household Energy database [48]. It draws together data gathered at national and sub-national levels in most countries using censuses and surveys (see Ref. [48] for measurement methodology). Although measuring energy use, the primary purpose for collecting the data is for their use as proxies for pollution in calculating health impacts (see for example [50,52]). Gross Domestic Product (GDP) per capita is used here as a measure of economic development; data which is frequently used in considering economic growth and trends [53]. Further details of the data can be found on the World Bank website [41].

3.2. Methodology

The aim here is to examine the causality link between GDP and solid fuel energy consumption. Previous studies have suggested that panel cointegration techniques are useful to identify causality, especially where relationships are not unidirectional or where time series data is limited [54]. Four stages were undertaken during the investigation. Firstly, the panel unit root tests for the series are performed to examine the stationarity properties of the variables — GDP and solid. Next, following the confirmation that the variables are integrated at order one I (1).i.e. after first differencing, cointegration tests are executed. Thirdly, based off of the results from the cointegration analysis stage, if the variables are cointegrated, the cointegration vector is examined utilizing Panel Fully Modified Ordinary Least Square (hereafter FMOLS) and Dynamic Ordinary Least Square (hereafter DOLS). Finally, a panel error correction model is developed to investigate the direction of causality.

3.2.1. Panel unit roots tests

Econometric studies such as [53,55,56] have used panel unit root tests to investigate the degree of integration between variables of interest. Accordingly, to fully examine the stationarity characteristics of the variables, we apply five different panel unit tests. The tests applied are: Levin, Lin and Chu (hereafter LLC); Im, Pesaran and Shin (hereafter IPS); Breitung; ADF and PP Fisher (hereafter MW) and Hadri panel unit root tests. The most commonly used panel unit root test is the LLC technique which is based on the Augmented Dickey—Fuller (hereafter ADF) test. LLC assumes that under both the null and alternative hypotheses, all groups have the same autoregressive (AR) coefficient [57]. As such, assumes a homogeneous panel.

The IPS technique extends on LLC but allows for heterogeneity by considering the use of averages of the ADF tests and likelihood ratio [58]. Thus, in comparison to LLC, fewer time observations are required for a higher test power[1] [59].

However, both the LLC and IPS techniques have the disadvantage of assuming independence across the cross-sectional of the panel units [59]. Therefore, to account for the possibility of cross-sectional correlation and probable spillage across countries, we apply the Breitung, MW and Hadri techniques. Unlike the LLC and IPS tests which apply bias-corrected estimators, the Breitung test uses unbiased estimators. Thus, it results in a higher test power [60,61].

In contrast to previously mentioned tests which are asymptotic, the MW test is a non-parametric analysis derived from the Fisher test [62]. It combines individual unit root test p-values to obtain results which are non-dependent on the lag lengths of individual ADF regressions. As a result, it has a higher test power in comparison to the LLC and IPS tests [62].

Finally, the Hadri test is a residual-based Lagrange Multiplier (LM) test where OLS residuals are obtained by regressing an output on a constant [63]. The null hypotheses for the various tests are as follows: both the LLC and IPS tests assume a unit root as the null hypothesis (thus non-stationarity); the Breitung null hypothesis assumes that the panel series have non-stationary differences. The MW tests also assume a unit root (non-stationarity) null hypothesis while the Hadri and Heteroscedastic consistent z-stat tests assume a no unit root null hypothesis (stationarity).

3.2.2. Panel cointegration

To examine the relationship between use of solid fuel and GDP, the panel cointegration tests created by Pedroni (1999, 2004) were used. The test uses heterogeneous panel and heterogeneous group mean panel test statistics to test for panel cointegration between variables [46,64]. The relationship is defined as follows:

$$GDP_{i,t} = a_{it} + \beta_i t + \delta_i solid + \varepsilon_{it} \tag{1}$$

where;

$$t = 1, \ldots., T; i = 1, \ldots., N$$

t represents time across period, T; i represents panel members across cross-section, N; α_{it} represents individual-specific deterministic time trends and ε_{it} represents estimated residual which demonstrates the deviation from the long-run relationship [46].

Seven statistics which are categorised into two sets are defined within this test. The *panel v-statistic*; *panel ρ-statistic*; *panel PP-statistic* and *panel ADF-statistic*, referred to as 'panel cointegration statistics', are based on the pooling of the residuals along the within dimension of the panel [46]. The *group rho-statistic*, *group PP-statistic* and *group ADF-statistic*, referred to as 'group panel cointegration statistics' are based on the pooling of the residuals along the between dimension of the panel [46].

Since the Pedroni tests assume cross-sectional dependence, we apply further cointegration tests. Kao and Fisher cointegration tests are used for robustness check. The Kao test (also residual based) is derived from the Engle-Granger procedure [65] while Fisher's test is a non-parametric test based on maximum likelihood [66].

All tests assume a null hypothesis of no cointegration.

3.2.3. Estimating the long run cointegration relationship

Following the detection of cointegration in the results from stage two, we proceed to evaluate the long-run relationship between solid fuel use and GDP. For this, we apply the panel Dynamic Ordinary Least Square (DOLS) and Fully Modified Ordinary Least Square (FMOLS) tests. Proposed by Mark and Sul, the DOLS test is a parametric asymptotically normally distributed test which adjusts errors through reinforcing the static regressor with the lags, leads and values of regressors in the first differences [67,68]. As such, degrees of freedom are lowered in the process. On the other hand, the FMOLS is a non-parametric test proposed by Pedroni [64,69] which considers correlation between the error term and the first differences of the regressors. Thus, it has fewer assumptions. As a result, although both methods produce consistent error estimates, studies have mixed opinions on which of the tests produces more robust results [65,70,71].

3.2.4. Panel granger causality tests

To investigate the direction of causality, we apply the Granger causality test to the observed long-run relationship. Two stages are involved in this process. Firstly, we evaluate the residuals from the DOLS and FMOLS model. Secondly, we fit the evaluated residuals into a vector error correction model. At this point, we test for the source of causality using the statistical results from the coefficients of the lagged dependent variables. We consider the speed of adjustment (coefficient) and significance (p-value) of the error correction variables to establish the existence (or non-existence) of long-run causality in the results.

The error correction model is designed as follows:

$$\Delta Solid = \alpha_{1i} + \sum^{z} L = 1\gamma_{1iL}\Delta SOLID_{it-L} + \sum^{z} L = 1\gamma_{1iL}\Delta GDP + \zeta_{1it} \tag{2}$$

$$\Delta GDP = \alpha_{2i} + \sum^{z} L = 1\gamma_{2iL}\Delta GDP_{it-L} + \sum^{z} L = 1\gamma_{1iL}\Delta SOLID + \zeta_{2it} \tag{3}$$

where; α_i, γ_i are adjustment coefficients; L is number of lags.Following this process, we investigate if a short-run causality relationship is present or absent.

4. Results

4.1. Panel unit roots results

A summary of the results from the various panel unit root tests for the model are displayed in Table 4. The illustrated results demonstrate the stationarity (or lack of) properties of the variables as constant, constant-with-trend and first differenced variables.

For the GDP variable (no trend), at level, the null hypothesis of a unit root cannot be rejected at 1% and 5% significance levels for all tests; excluding the Hadri and Heteroscedastic consistent z-stat tests which have the null hypotheses of no unit root. For the solid variable, the null hypothesis of a unit root cannot be rejected at 1% and 5% significance levels for LLC and IPS tests. At first difference, for both variables, the null hypothesis for all tests can be rejected at 1%, 5% and 10% significance levels.

As such, the panel unit root condition can be concluded, the variables deemed initially non-stationary but stationary when integrated at order one (I(1)). Thus, fulfilling the conditions required for cointegration analysis.

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[1] Power here refers to the probability of rejecting the null when it is false.

Table 4
Results for panel unit root tests for GDP and Solid Fuel Usage.

	Tests	Null: Unit root					Null: No unit root	
		LLC	IPS	Breitung	ADF - Fisher	PP - Fisher	Hadri	z-stat
Variable								
Level	GDP	−0.6391 (0.2614)	4.7989 (1.0000)	–	39.0981 (1.0000)	38.3720 (1.0000)	16.8465 (0.0000)	16.5608 (0.0000)
	GDP (trend)	−3.7260 (0.0001)	−1.2713 (0.1018)	−0.6506 (0.2577)	103.727 (0.0936)	125.063 (0.0038)	11.9059 (0.0000)	14.0522 (0.0000)
	SOLID	3.4614 (0.9997)	1.4778 (0.9303)	–	154.975 (0.0000)	220.855 (0.0000)	19.4236 (0.0000)	20.9639 (0.0000)
	SOLID (trend)	−22.0322 (0.0000)	−32.4615 (0.0000)	−1.2549 (0.1048)	465.681 (0.0000)	425.702 (0.0000)	14.3973 (0.0000)	31.8515 (0.0000)
First difference	GDP	−11.4345 (0.0000)	−9.8955 (0.0000)	–	257.387 (0.0000)	381.983 (0.0000)	5.64430 (0.0000)	5.15373 (0.0000)
	GDP (trend)	−12.4084 (0.0000)	−6.9440 (0.0000)	−6.2492 (0.0000)	204.713 (0.0000)	383.814 (0.0000)	34.3556 (0.0000)	30.1044 (0.0000)
	SOLID	−28.5899 (0.0000)	−31.8400 (0.0000)	–	462.855 (0.0000)	498.473 (0.0000)	11.9748 (0.0000)	11.0287 (0.0000)
	SOLID (trend)	−24.2711 (0.0000)	−32.0677 (0.0000)	−13.521 (0.0000)	417.153 (0.0000)	405.481 (0.0000)	11.5163 (0.0000)	12.0685 (0.0000)

Table 5
Results for Pedroni residual cointegration tests.

Tests	Within panel statistics			Between panel statistics		
	Type	Statistic	p-value	Type	Statistic	p-value
GDP, SOLID	panel v-statistic	0.2938	0.3845	group rho-statistic	1.5652	0.9412
	panel rho-statistic	−2.9587	0.0015	group PP-statistic	−1.4196	0.0779
	panel PP-statistic	−2.5640	0.0052	group ADF-statistic	−4.8626	0.0000
	panel ADF-statistic	−3.8290	0.0001			
GDP, SOLID (weighted statistic)	panel v-statistic	−1.4410	0.9252			
	panel rho-statistic	−0.9927	0.1604			
	panel PP-statistic	−2.9727	0.0015			
	panel ADF-statistic	−5.3892	0.0000			

4.2. Panel cointegration results

In Table 5, the results obtained from the Pedroni within and between cointegrated tests are presented. For the unweighted cointegration tests, out of seven tests, we can strongly reject the null hypothesis of no cointegration in four tests (at 1% significance levels) whilst due to its close p-value, we could consider a 5th test as marginal.

At 10% significance level, we can strongly reject the null hypothesis of no cointegration in five tests. For the four weighted statistic tests, the null hypothesis of no cointegration cannot be rejected for the first two tests but can be strongly rejected for the panel PP and ADF statistic tests.

As such, we consider the strong possibility of a long-run relationship between household use of solid fuels and GDP per capita. Accordingly, for robustness check, we consider two further cointegration tests to validate these results.

Table 6 presents the results from Kao's residual panel cointegration test. The obtained result strongly rejects the null hypothesis of zero cointegration at 5% and 1% significance levels. Thereupon, confirming the presence of a long-run relationship amongst the variables. Nonetheless, we perform an additional cointegration test to prove (or infirm) the obtained outcomes.

Table 6
Results for Kao's residual cointegration test.

Model	ADF	p-value
GDP, SOLID	−4.268	0.000

In Table 7, we present the results from the Fisher-type panel cointegration tests. For the fisher tests, the cointegrating elements are expressed as 'ce'. The tests are then computed under the null hypothesis H_0 : ce $\leq$ c, alternative hypothesis $H_1 : ce_0 >$ c, for the trace test and null hypothesis $H_0 : ce_0 =$ c, alternative hypothesis $H_1 : ce_0 >$ c for the max-eigenvalue test. Similar to the Kao's cointegration test, the results obtained from the two analyses: the trace and max-eigen tests strongly reject the null hypotheses of zero cointegration at 1% significance level: further supporting the existence of cointegration amongst the variables.

Therefore, considering the results obtained from the four (4) tests, the premise of cointegration between the variables is concluded. This implies that the variables move in unison in the long run.

The next stage of the analysis involved evaluating of the long-run elasticities.

4.3. Long run cointegration results

Table 8 presents the long-run elasticities obtained from the DOLS and FMOLS models (using 'Solid' as the independent variable). As previously stated in section 3.2.3, the DOLS produces less robust results due to its tendency to add leads and lags to variables. Thus, reducing the degree(s) of freedom. Yet, only DOLS effectively allows for the estimation of trend and direction of causality. As such, although we consider both results, we interpret only the DOLS results. The results obtained for the DOLS model show a negative and significant (at 1% level) elasticity, between solid fuel use and GDP per capita. The obtained results show a statistically

Table 7
Results for Fisher-type cointegration tests.

Null hypothesis	Fisher stat* (trace test)	p-value	Fisher stat* (max-eigen test)	p-value
ce = 0	1255	0.000	727.6	0.000
ce ≤ 1	180.6	0.000	180.6	0.000

Table 8
Results from DOLS and FMOLS tests.

	Models	
	DOLS	FMOLS
Co-efficient	−84.6612	−45.77895
Std.Error	16.3579	11.03649
t-statistic	−5.1756	−4.1480
p-value	0.0000	0.0000

significant, negative effect on GDP per Capita and can be interpreted as such. Overall, the estimates of our analyses indicate that there is a strong and significant long-run link between household use of solid fuels and GDP per capita. They indicate that an increase in household use of solid fuels, has a negative impact on GDP per capita.

4.4. Panel granger causality results

Following establishing that economic development (GDP per capita) is cointegrated in the long-run with the household use of solid fuels, we investigate the causality between the two variables, using the optimal lag structure of 1: based on the Akaike and Schwarz criteria. The results in Table 9 show the outcomes from the Granger causality test for the optimal lag structure (i.e. a lag of 1 year).

The results highlight the fact that when a long-run causality relationship running from household use of solid fuels to GDP per capita is considered, the null hypothesis of zero causality cannot be accepted at a 5% significance level for the first lag and at 1% significance level for further lags. For a long-run causality relationship running from GDP per capita to household use of solid fuels, for the first lag, although marginal at 10% significance level, the null hypothesis of no causality cannot be rejected at 5% or 10% significance levels. For the second lag, the null hypothesis can be rejected at 5% significance level but cannot be rejected at 1% significance level. As such, considering that the first lag is deemed the optimal lag, it can be inferred that the long-run relationship runs in only one direction: from household use of solid fuels to GDP per capita.

4.4.1. Short-run causality

Finally, we consider the short-run relationship between the two variables. Table 10 presents the results from the short run causality test. The results show that the null hypothesis of no short-run causality can be rejected for the 'Solid' dependent model but cannot be rejected for the 'GDP' dependent model. Considering that we can accept the 'Solid → GDP' hypothesis at 1%, 5% and 10% significance levels, it can be inferred that this result implies that there exists a strong and significant short-run causal relationship running from solid fuel to GDP.

Table 9
Results for Granger causality test (L = lags).

Dependent variable	f-statistic	p-value	Sense of causality
GDP			
SOLID (L = 1)	4.89562	0.0273	SOLID → GDP
SOLID (L = 2)	3.41759	0.0135	
SOLID (L = 3)	3.19592	0.0076	
SOLID			
GDP (L = 1)	2.69322	0.1013	GDP → SOLID
GDP (L = 2)	3.12592	0.0447	
GDP (L = 3)	6.57827	0.0070	

Table 10
Short-run causality results.

Dependent variable	Chi-square	p-value	Sense of causality
SOLID	2.184711	0.3354	GDP → SOLID
GDP	9.712422	0.0078	SOLID → GDP

On the whole, the link between household use of solid fuels and GDP per capita is identified by an uni-directional causality running from solid fuels to GDP per capita in both the long-run and short-run dynamics.

5. Conclusion and policy implications

This paper has investigated the empirical evidence of the link between lack of access to clean cooking fuels and economic development: using data from 46 sub-Sahara African countries, for the period of 2000–2015. GDP per capita and percentage of population depending on traditional (solid) fuels were used as variables for the analyses.

For this purpose, we have utilised the panel unit roots tests, panel cointegration and causality methods. The robustness of the results at each stage of the analyses, was tested by utilizing multiple models per stage. In terms of the short-run causality, our estimations indicate that the use of solid fuels has a statistically significant impact on economic development in the short-run for sub-Saharan Africa. An increase in the household use of solid fuels such as coal, animal dung, dried crops, etc., for cooking and/or heating, would probably impact on GDP per capita.

With statistically significant error correction terms, our estimations show that the use of solid fuels negatively impacts on GDP per capita. In both the short-run and long-run analyses, our results indicate negative growth hypotheses in the solid fuels-economic development scenario for sub-Sahara Africa. Hence implying that the household use of traditional (solid) fuels for cooking and/or heating is an inhibitor to economic development within the region. This translates that the economic performance within the region is partly influenced by the amount of population having to rely on solid fuels for day-to-day activities. Although the economic development of a country is a complex dynamic influenced by several factors (and that of a region, even more complex), the level of productivity within the country (and in this case, region) still remains a large influence on the economic performance of the country. At the most simplistic level, although arguably the use of solid fuels would contribute to economic inputs (for example, serve as a form of revenue or employment for the unskilled), one could still associate the reduced productivity caused by household use of solid fuels to reduced economical productivity.

Furthermore, in the case of sub-Saharan Africa, where most countries are considered economically low-income, the hypothesis that through rising economy or better still, improved economic conditions: for example, in the way of increased household incomes, the household use of solid fuels can be addressed, is rejected by the causality estimations. As such, based on the results, our intended questions can be answered as such: enhanced economic development might play a role influencing the nature of household use of traditional (solid) fuels but ultimately, household use of traditional (solid) fuels plays a crucial role in achieving said enhanced economic development.

From a policy perspective, the implication of these findings is that changes in the household energy profile have a significant effect on changes in economy in sub-Saharan Africa. In the context of the hypotheses discussed in section 2, our results indicate the existence of a negative-growth hypothesis between household use of solid fuels and economic development within the region. Hence, although in growth hypothesis scenarios, energy conservative policies: temporal or permanent, might hinder economic development; based on these results, this might be different in relation to sub-Saharan Africa. Due to the negative link, solid fuels conserving measures might not only be beneficial in preventing the inimical impacts, but also beneficial for the socio-economic development of the region. However, implementing solid-fuels reducing policies within a region where most of the population have little-to-no access to modern alternatives, might not be an ideal policy strategy. Further implication of our findings show that sub-Sahara African countries require for economic development, to increase the access to modern fuels for cooking and/or heating. Although the requirement of a hefty capital investment can be anticipated: due to declining and/or lacking infrastructures; the substantial impacts of the current situation on socio-economic development, as well as environmental sustainability, make these investments necessary and ultimately, inevitable.

Lastly, it is worth noting that the nature and effectiveness of policies will differ based on the levels of development of the countries; country-specific barriers, amongst other factors. And although we have not explored the various barriers to attaining this goal; from a policy perspective, to aid the progress towards clean cooking fuels, it can be anticipated that there is a need for policies aimed at addressing barriers to be implemented alongside modern energy accessibility policies.

All in all, it can be inferred that it is beneficial for sub-Saharan African countries to continue to strive from household use of solid fuels to clean energy - as this is likely to reinforce the much needed economic development. Finally, the relationship between the use of solid fuels for cooking and economic development needs to be further investigated. As a starting point, more attention needs to be placed on data collection. For example, although we have used panel national data in our analyses, it would be interesting to analyse the relationship using sub-national data. Sub-Saharan Africa is known to have a complex dynamics: there are vast differences across and within the countries. By using sub-national data, it might be possible to uncover some of these complex relationships within the countries.

To conclude, certainly, a better understanding of the underlying factors contributing to this issue is fundamental if the situation is to be improved. As such, more research in the area of cooking and/or heating fuels (particularly underlying barriers to access) in developing countries is necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.119770.

Credit author statement

Ifeoluwa Garba: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. Richard Bellingham: Supervision.

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