Asian Development Policy Review
ISSN(e): 2313-8343
ISSN(p): 2518-2544
DOI: 10.18488/journal.107.2020.83.214.235
Vol. 8, No. 3, 214-235.

URL: www.aessweb.com

SUSTAINABLE ENERGY DELIVERY FOR AFRICA'S CHANGING CLIMATE: AN ECONOMIC ASSESSMENT

Jonathan D. Quartey

Department of Economics Kwame Nkrumah University of Science and Technology Kumasi, Ghana.
Email: jdquartey@yahoo.com Tel: +233-244206280

Article History
Received: 25 June 2020
Revised: 3 August 2020
Accepted: 7 September 2020
Published: 18 September 2020

Keywords
Africa
Climate change
Energy transition
Electricity
Fossil fuel
Hotelling Rule
Renewable energy
Solar photovoltaic.

JEL Classification:
Q41; Q42; Q54; Q58.

ABSTRACT

This paper assesses Africa's energy future in a changing global climate to inform development policy. In the midst of economic and energy challenges, coupled with COVID-19 pandemic recovery, Africa is expected to meet global climate obligations. While it makes sense to develop climate resilient economies, Africa appears stuck in its pre-climate change energy delivery systems. The economic, social and environmental consequences of this stagnation are suboptimal for the continent, calling for urgent transition to more sustainable energy delivery. The study analyzed fossil fuel use in Africa from 1960 to 2016, based on a modified Hotelling Rule. Through time series data, the sustainable marginal cost of energy for Africa was estimated. The study further derived the optimal point in time when Africa should switch from fossil fuels as a main source of electricity generation to renewable energy, due to climate change. The study finds more than 70 percent increase in the marginal cost of fossil fuel compared to a cumulative reduction of 80 percent in the marginal cost of solar photovoltaic over the study period. Also, the switch point to renewable energy as the main source of electricity in Africa was found to be 2003. For sustainable delivery of energy in Africa, the study recommends policies to internalize the externalities of fossil fuel, backed by recovery subsidies to make up for the loss of welfare from fossil fuel use, and to create an enabling environment for a speedy energy transition in Africa's changing climate.

Contribution/ Originality: The paper's primary contribution is finding that Africa's optimal switch period from fossil fuel to renewable energy as the main source of electricity generation was 2003. It determines the backstop energy resource for Africa's optimal energy transition, to improve welfare and contribute to 1.5^0 Celsius cap for global climate stability.

1. INTRODUCTION

Recent trends in clean energy demand appear to be driving a major transformation in global energy delivery. The 75% growth in human populations globally in the past four decades came with increasing urbanization and more than 250% growth in electricity generation (IRENA, 2014). A continuation of this growth trajectory is expected to continue, particularly in developing countries.

The increased urbanization is estimated to cause 70% growth in global electricity production by 2030. However, this growth in electricity generation will be coming at a cost to the quality of the world's environment, since the average emissions intensity of generating electricity has seen no significant change over the past two decades (Harris & Roach, 2018; IRENA, 2014).

Africa's mean real output was estimated at 4% growth between 2017 and 2019, with six of its economies coming within the 2018 top ten fastest growing globally (AfDB, 2016; World Bank, 2018). An expected consequence of this growth, coupled with increasing population is the doubling of energy demand in Africa by 2040 (IRENA, 2019).

The increased demand for energy services will have to be met with minimal impact on the earth's life support system. The promising performance of renewable energy in this direction makes it appealing to Africa. However, the length of the transition as well as the policy response from African economies remain largely uncertain (IRENA, 2014). The fact that future electricity availability could be enhanced by abundance of renewable energy resources, provides hope for improvement in Africa's energy future, since such resources abound on the continent.

Climate change effects could however jeopardize the economic and technical advantages in the use of renewable energy in Africa, increasing marginal cost of electricity generation. Climate change introduces new dynamics for costs, safety, output and access to electricity in general and renewable energy in particular. Changes in meteorological factors are a threat to electricity production and infrastructure, with attendant setbacks for livelihoods and economies in Africa. However, Urban and Mitchell (2011) affirm that research in this direction has not been forthcoming.

1.1. Background of the Study

In Africa, two in three people lack access to electricity, thus hindering the provision of basic health services, education for children and business competitiveness. Even some economies which have electricity, have to struggle with poor quality services with unstable supply, consuming relatively little and paying high tariffs for electricity. The existing situation calls for efforts to achieve the global goal to attain sustainable energy for all by 2030 (World Bank, 2017).

The World Bank estimates that US$19.6billion will have to be invested every year in Africa till 2040 to realize the needed electricity target of 292 gigawatts (GW). The current electricity disruptions costs the continent 1 to 5 percent of gross domestic product, coupled with an excessively low capacity to produce electricity (World Bank, 2017).

While the serious limitation of access to electricity persists, Africa has at its immediate disposal over 50 percent of global renewable energy (AfDB, 2016; Kirchner & Salami, 2014) with less than 10 percent in use (AfDB, 2016; UNIDO, 2009). Wu, Deshmukh, Ndhlukula, Radojicic, and Reilly (2015) reveal that the African Clean Energy Corridor region has an aggregate economic potential of up to 15,334GW of solar photovoltaic.

Within the past three decades, the world economy had doubled, resulting in a 40% rise in global carbon emissions since 1990 (Kyoto protocol reference year). Increasing opportunity costs are showing in the extraction costs and technical challenges of key resources like oil. While physical scarcity may not be the limiting factor, opportunity costs related to the complex supply chains that lead from geological processes to the refined raw materials have become issues of concern for the stability of fossil fuel based energy systems (BP, 2013).

The Intergovernmental Panel on Climate Change (IPCC) (2014) projects that higher temperatures, hurricanes and forest fires will occur more frequently with higher intensity and length. Jaglom (2014) found that by 2050 electricity generation costs would rise by 14 percent per annum as a result of climate change. Changes in climatic conditions are expected to cause substantial damage to electricity production and transmission installations, with serious effects on economic conditions in the future (Choleta, 2015; Reed, Powell, & Westerman, 2010).

1.2. The Problem

The precarious energy situation of Africa, coupled with extreme climatic situations appear to be causing further deterioration of poverty and progress on the continent. This is because recent trends show that natural resource constraints have the tendency to change the way the world produces and uses energy. Thus to make the right choices for sustainable development, energy's relationships with the natural resources which directly support life must be understood. While it is evident that climate change could further constrain Africa's growth through its effect on energy resources, research in this area has not been readily available.

Existing studies have been restricted to themes on demand for energy and the effect of some climatic elements, particularly temperature on the demand for energy, leading to findings which recommend adaptation measures (Ahlborg, Boräng, Jagers, & Söderholm, 2015; Akar, 2016; Brennan et al., 2008; ESMAP, 2011). Some studies have also concentrated on climate change impacts on energy sectors in general (Brennan et al., 2008; Erdal, 2015; Intergovernmental Panel on Climate Change (IPCC), 2007a, 2007b, 2014; IRENA, 2016) without paying attention to the varying climate conditions. However, differing and extreme climatic occurrences could compromise energy security and supply, creating substantial socio-economic effects (Urban & Mitchell, 2011).

Research on the economics of changing climatic elements on the production of renewable energy has been largely overlooked (Eyraud, Wane, Zhang, & Clements, 2011). Within the domain of renewable energy, studies have mostly been on the various technologies (Brunnschweiler, 2009; Pohl & Mulder, 2013). Some isolated studies which examined the impacts of climate change on renewable energy generation (Jerez et al., 2015; Pašičko, Branković, & Šimić, 2012) did so with respect to Europe. Hence, the knowledge gap pertaining to climate change impact on Africa's renewable energy allocation (Lokonon & Salami, 2017).

This study therefore aims at informing policy on the way forward for harnessing clean energy in Africa's changing climate. Specifically, it sought to assess the role of climate change in electricity provision and to compare trends of the marginal costs of fossil fuel and renewable energy in Africa. It further sought to identify the backstop energy resource capable of replacing fossil fuel and to determine the switch point between fossil fuel and renewable energy in Africa.

The study hypothesizes the existence of significant difference between the rate of change of the marginal cost of fossil fuel used in Africa and the marginal cost of renewable energy available to Africa. The following section explains the policy relevance of the study, followed by a review of some pertinent literature. An analytical framework and analysis of relevant data and scenarios then follow. A discussion of the findings come next. This is followed by some recommendations on the way forward for Africa, and a concluding statement.

1.3. Policy Relevance

Policy analysis to explain climate change effects for renewable electricity production has largely been ignored by most researchers (Urban & Mitchell, 2011). Given the growing contribution of renewable energy globally, significant changes are occurring within the renewable energy industry calling for more policy attention and research.

The traditional feature of energy sectors reveals domination of large utilities. However, recent developments show more decentralization and diversity. The German example indicates that households and farmers control almost 50% of all renewable energy, with only 12% in the hands of utilities. Expected changes remain significant due to smart and storage technologies creating capacity for off-grid systems and more flexibility in the sector (IRENA, 2014). Since the current transition calls for new and innovative ways of managing energy, policy makers are expected to do a lot to either promote or hinder the ongoing transformation.

Investors in renewable energy require well-structured systems which recognize their contribution. The varying needs for the thriving of renewable energy systems will have to be identified and addressed through appropriate policy. Thus policy makers need to figure out a holistic framework which will harness renewable energy to promote secure electricity availability without hurting jobs and the natural environment (IRENA, 2014).

Countries may differ in their choices, based on specific social, political and economic circumstances, which may be guided by engineering requirements for efficient delivery. The choices made will have different implications for availability of energy, the economy and the environment. High fixed costs due to the nature of technologies and infrastructure could render wrong choices damaging for economies and human welfare. This makes it essential to provide policy makers with all available relevant knowledge to enable them make the best choices.

Thus the policy implications of this paper revolve around African policy makers' recognition of the urgency and benefits of practically transiting from a mainly fossil fuel based electricity sector to a mainly renewable resource based electricity sector. This will as a consequence require integrated planning and execution of appropriate state and private sector investments in renewable energy infrastructure and systems of production, distribution and consumption, to deliver the benefits of the transition. While policy implications are tailored towards benefit derivation, there are also costs inherent in Africa failing to act in good time to benefit from the transition. The longer the delay, the more costly the tradeoffs will be for Africa.

2. SOME CONCEPTUAL ISSUES

2.1. Future Price of Renewable Energy

The perception that energy from fossil sources come at the least cost is being challenged by economic reality, promoting high effective demand for energy from renewable sources (Timmons, Harris, & Roach, 2014). Levelized cost of energy (LCOE) values provides a platform for comparison between different energy sources. These costs capture the real present value involved in the construction and operation of a system within a proposed operational period. The wholesale electricity price is usually considered the reference point for cost competitiveness (Timmons et al., 2014). The International Energy Agency (IEA) found that hydroelectricity and biomass had attained this requirement by 2007 (International Energy Agency (IEA), 2007).

As a result of a 90% decrease in prices of modules between 2010 and 2019, the weighted-average LCOE of utility-scale solar PV's globally decreased by 82%, from USD 0.378/kWh to USD 0.068/kWh. This decrease coupled with a decreasing cost of balance-of-system (BoS) resulted in a 79% fall in the weighted-average installation costs within the period (DOE, 2012; IRENA, 2020).

With respect to residential PV, the decrease in LCOE was between 42% and 79%, while commercial systems up to 500 kW, saw the least LCOEs of USD 0.062/kWh between 2010 and 2019. Also, 75% of onshore wind systems not supported financially produced electricity at significantly lower costs than the cheapest fossil fuel-fired system in 2019 (IRENA, 2020).

Globally, renewable energy generation capacity increased by more than 300%, from 754 gigawatts (GW) to 2 537 GW between 2000 and 2019 (IRENA, 2020a). In 2019, an additional generation capacity of 176 GW of new renewable energy was achieved. This consisted of 97GW of solar photovoltaic (PV) capacity increase, 54GW onshore wind power, 12 GW hydropower, 6 GW bioenergy and 5 GW offshore wind capacity. Also included was about 700 megawatts (MW) of geothermal capacity and concentrating solar power (CSP) of 600 MW. Thus, 72% of the net capacity expansion of all energy generation sources in 2019 was due to new capacity additions from renewables. This means since 2015 renewables represented over 50% of additional net capacity (IRENA, 2020a). Thus, while the capacity of renewable energy to fully support modern economies at reasonable expense is no longer in doubt, the remaining hindrance becomes its funding and speedy rollout (IRENA, 2014).

2.2. Equimarginal Principle and Renewable Energy

The normal trend to find about marginal costs of any finite renewable energy resource is that they will be rising in any economy. To be economically efficient in energy delivery, the marginal costs of an economy's sources of energy must all be equal. The reason is that, any energy source with a higher marginal cost than one in use will be considered too costly and rejected. Also, any energy source with a lower marginal cost than the one in use will be preferred to the one in use, since it would be cheaper than the one in use. Thus, economic stability will only be possible where all energy resources in use have the same marginal cost, making a mix of different renewable sources economically relevant (Tietenberg & Lewis, 2012; Timmons et al., 2014).

2.3. Net benefits of Renewable Energy

Extensive support currently exists for renewable energy as a promoter of economic development in a safe human and natural environment, based on net benefit computations. Benefits ranged between 200% and 300% above costs in a Japanese study targeting an average of 15% renewable energy use by 2030. The realized benefits included economic ripple effects, carbon emission reduction and savings from reduced fossil fuel imports. The experience of Spain in 2010 and Germany in 2012 showed the avoidance of USD 2.8 billion and USD13.5 billion of fossil fuel imports respectively for using renewable sources of energy. Even with fossil fuel-exporting countries, domestic deployment of renewables makes more fossil fuel available for export (IRENA, 2014).

Realized employment from the renewable energy industry was about 6.5 million in 2013, as well as making access to electricity easier and cheaper for many deprived communities, thereby improving the livelihoods of several deprived people. While fossil fuel electricity is responsible for 40% of carbon dioxide emissions from human induced sources, renewable energy are between 10 and 250 times less carbon intensive (IRENA, 2014). Thus the climate security the world desires is highly possible with a speedy transition to renewable energy (Jones, Graham, Tunbridge, & Ilas, 2020).

2.4. External Costs

The production and use of fossil fuels have always been associated with high levels of costs borne by communities, most of who never share in the profits of the industry. To attain social efficiency, which is a prerequisite for real welfare improvement, pricing every source of energy must capture its full social costs. If this principle had been applied, the needed transition to renewables would have been fully operational by now. Because externalities have not been internalized for fossil fuel, it becomes too cheap to produce fossil fuels, since a considerable portion of the real costs are borne by society.

Owen (2006) found the external cost of coal to be between 2 and 15 Eurocents per kilowatt-hour. Jacobson and Delucchi (2011) found these external costs to be 6 US cents per kilowatt-hour, while those associated with renewable sources of energy were less than one Eurocent per kilowatt-hour. This implies the current supposed cost advantage of fossil fuels over renewables energy are largely due to the non-inclusion of external costs in pricing fossil fuels (Ogden, Williams, & Larson, 2004).

This presents external costs as the most important stumbling block to the current energy transition. If the prices are not corrected for external costs, the bad economics associated with consuming fossil fuels as against renewable energy will still persist. The inclusion of external costs makes all renewable energy sources less expensive than fossil fuels (Jacobson & Delucchi, 2011; Timmons et al., 2014). This shows the good economic reasoning behind promoting the transition to renewable sources of energy (Timmons et al., 2014).

The International Monetary Fund (IMF) (2019) found that if external costs had been added to fossil fuel prices in 2015, reductions of 28% in global CO_2 emissions would have been achieved, deaths due to fossil fuel air pollution would have declined by 46%, and revenues from taxation would have increased by 3.8% of global GDP. Also, the derived net economic benefits would have been 1.7 percent of global GDP (International Monetary Fund (IMF), 2019).

2.5. Subsidies

Whitley et al. (2018) found state fiscal support for fossil fuels in over 50 economies globally, amounting to about US$100 billion yearly in 2015 and 2016. The International Monetary Fund (IMF) (2019) labelled the underpricing of fossil fuels as pervasive and substantial. It cites the case of country-level coal prices as typically not up to 50% their fully efficient levels in 2015. The fund also found road fuel prices to be enjoying subsidies of over 20% their efficient values. Globally, energy subsidies stood at US$4.7 trillion (6.3% of global GDP) in 2015 and $5.2 trillion (6.5% of global GDP) in 2017.

In 2015, China surpassed all countries by far with the highest subsidy of $1.4 trillion, the United States came next with $649 billion. In addition, Russia subsidized energy with $551 billion, European Union $289 billion and India $209 billion. Globally, fossil fuels received subsidies of between 10% and 44% in 2015. Subsidies continue to rise for fossil fuels globally (International Monetary Fund (IMF), 2019).

These statistics clearly indicate that fossil fuel prices are generally perceived to be competitive because they are supported by subsidies which amount to several billions of dollars to promote their use. The exclusion of fossil fuel subsidies could thus render fossil fuels incapable of competing with renewable sources of energy. Thus the real marginal cost of fossil fuel (RMC_{FF}) is generally supposed to be

$$RMC_{FF} = CMC + MEC + MCS \qquad (1)$$

Where CMC is the current perceived marginal cost of fossil fuels,

MEC is the marginal external cost of fossil fuels.

MCS is the marginal cost of subsidizing fossil fuels.

This means the current perceived marginal cost of fossil fuel used by policy makers to allocate energy resources is $CMC = RMC_{FF} - MEC - MCS$, which falls short of the requirement for optimal allocation.

Thus, identifying RMC_{FF} becomes one of the most crucial requirements for optimal allocation of energy resources for electricity, especially in Africa.

3. THE HOTELLING RULE AND OPTIMAL ENERGY ALLOCATION

Exhaustible resources like fossil fuel in the ground are generally considered as capital assets. Efficiency requires the absence of any gain in moving resources from one asset to another, this suggests equal returns to all the assets. If it is possible to obtain a gain by shifting from one asset to another, competitors will enter the industry to compete for the extra gain till it is no longer possible to have any excess gain from any asset. This is the point where there will be no tendency to shift from one asset to the other, this equilibrium depicts the point where efficiency is attained. The marginal cost of an asset is the additional cost of obtaining one more unit of the asset, while the price is what is obtained from the sale of that unit of the asset. If the price exceeds the marginal cost, then the remaining value accounting for the difference will be value inherent in the asset, which is called the royalty. Hotelling (1931) proposed that extraction should be divided within time periods such that the royalty rises at the (common) rate of interest (Hotelling, 1931).

Where p_1 is the current price of fossil fuel, p_0 is the initial price of fossil fuel, r is the rate of interest and MC is the marginal extraction cost of fossil fuel, the Hotelling Rule can be stated in symbols as:

$$(p_1 - MC) = (p_0 - MC)(1 + r) \qquad (2)$$

This provides the following price time path

$$p_1 = MC + (p_0 - MC)(1 + r) \qquad (3)$$

For many time periods the price of fossil fuels becomes

$$p_t = MC + (p_0 - MC)(1 + r)^t \qquad (4)$$

With time, the royalty assumes a greater proportion of the marginal cost of extraction, causing a rise in price at the interest rate. The fact that price rise over time will have an upper limit then becomes an issue.

There will be a price limit at which the quantity demanded falls to zero. More generally, it could be supposed that the limit will be determined by the price of a substitute, referred to as the "backstop" energy. This substitute offers the same service as fossil fuels and occurs in abundance guaranteed for the very long term.

Assuming solar energy is this substitute with a marginal cost equivalent of MC_b dollars per barrel of fossil fuel. Due to its abundance, the substitute will have no royalty, making the marginal cost equal to its price, which then becomes the upper limit for the price of fossil fuels.

Where T, is the switch date to the substitute from fossil fuels, Equation 4 becomes:

$$p_T = MC + (p_0 - MC)(1 + r)^T \tag{5}$$

Since $p_T = MC_b$, we have

$$(p_0 - MC) = \frac{(MC_b - MC)}{(1+r)^{T-1}} \tag{6}$$

Substituting the royalty at t = 0, which is $(p_0 - MC)$ into Equation 3, the price of fossil fuel at any time $t < T$ is expressed in terms of the marginal cost of the substitute and the marginal cost of fossil fuel;

$$p_t = MC + \frac{(MC_b - MC)}{(1+r)^{T-1}} \tag{7}$$

Where the royalty rises at rate r to $MC_b - MC$ and the price rises to MC_b at time T.

Substituting the expression for MC from Equation 1, the price of fossil fuel becomes.

$$p_t = CMC + MEC + MCS + \frac{(MC_b - (CMC + MEC + MCS))}{(1+r)^{T-1}} \tag{8}$$

This paper argues that climate change has a significant influence on the values of CMC, MEC, MCS, MC_b, and r. Thus p_t is subject to climate change risks, requiring Africa to respond appropriately for optimal allocation of renewable sources of electricity. Some empirical considerations necessary for Africa's optimal response are discussed in the following section.

3.1. Some Empirical Issues

From price data of several goods spanning 1870 to 1957, Barnett and Morse (1963) examined the effect of natural resource scarcity on economic growth through higher pricing. They found however, that prices of mineral resources did not show any significant rising trend over time. Following the finding, Smith (1979) employed data from 1900 to 1973 and greater statistical sophistication to evaluate the study. His finding showed no statistically significant stable time trend. This led him to conclude that detailed analysis of various natural resources was necessary for meaningful decisions regarding natural resource scarcity.

A study by Slade (1982) to fulfil the recommendation of Smith (1979) examined price trends between 1870 and 1878 of 11 main metals and fuels. Her finding showed a bottom out price series in the 1960s beginning to turn upwards in the 1970s. Following her finding, Slade (1982) developed a modified Hotelling Rule model to capture the effects of both cost-reducing technological change and cost-increasing degradation effect. The eventual outcome of the findings indicated that the cost-increasing effect of the Hotelling Rule overcame the cost-reducing effect of technological change. Thus overall, her model confirmed the consistency of U-shaped price paths with the Hotelling Rule.

Moazzami and Anderson (1994) used the same type of data as Slade (1982) in their study. They made use of additional years of data and allowed for short-run deviations from the long-run hypothesized trend to test whether the proposed long-run relationship was valid. Their findings showed that only a long-run relationship existed between nominal resource prices and changes in the price index, the data also supported the hypothesis of a U-shaped trend for most of the price series.

Svedberg and Tilton (2006) used inflation bias to adjust standard deflators downwards found the adjusted real price of copper following a statistically rising trend from 1870 to 2000, and falling over time when unadjusted deflators are used. This study, together with that of Moazzami and Anderson (1994) suggest the need for further examination of results from the use of relative prices for nonrenewable resources allocation decisions.

Also, Livernois (2008) asserts that the findings of Lee, List, and Strazicich (2006) reflect the current state of knowledge regarding the trend of nonrenewable resource prices. With respect to the price series for natural gas and petroleum, the trend followed a V-shape rather than a U-shape path. It also came out that even though prices went down by 1990 and about a decade after, all of the prices with the exception of coal showed dramatic increases after 2001, again falling in tune with the Hotelling Rule.

It is worth noting that many prices from exhaustible resources have not behaved according to the simple Hotelling Rule (Chari & Christiano, 2014). It has been shown that current extraction creates a negative effect, degrading the quality of remaining reserves and increasing the cost of extracting them in future. A strong degradation effect could lead to a decline in scarcity rent, in a competitive equilibrium. This makes the cost of extracting the remaining resource the constraint, not how finite the resource is (BP, 2013; Livernois, 2008).

It is probable that the world may never witness the physical exhaustion of any exhaustible resource. However, if a time comes when consumers are willing to pay less than further extraction costs, then economic exhaustion will have occurred. In such a situation, scarcity rent actually becomes zero. The implication of this for developing countries whose economies are highly dependent on extractive industries is very grave.

The Hotelling Rule, irrespective of the above modification remains the underlying theoretical framework for understanding the evolution of nonrenewable resource allocation (Livernois, 2008). Chari and Christiano (2014) suggest that the specification of the extraction costs could be the root cause of some studies not confirming royalty rising at the rate of interest, based on occurrences in the resource market. This paper modifies the perceived extraction cost used in most studies by specifying the extraction costs as shown in Equation 1.

4. METHOD OF STUDY

4.1. Research Design

The study analyzed World Bank data from 1960 to 2016 obtained from the World Development Indicators, to estimate a relationship between Africa's electricity future and climate change. The Hotelling Rule, as discussed in the previous section was used to confirm the suitability of the backstop energy source. It was also used to determine the switch point between fossil fuel and renewable energy sources in Africa.

Scenario building was used to assess the effects of climate change on various energy sources in Africa. These scenarios represented possible changes within the global environment due to anthropogenic factors which could alter the capacity for electricity availability. Each scenario was made up of a change in one relevant meteorological variable, as well as the outcomes for each source of electricity generation brought about by the change. The factors considered were; temperature increase, changes in rainfall, droughts, glacier melting, floods, increased frequency of storms and changes in wind, changes in solar radiation and changes in global conditions that could cause a global lockdown like COVID-19.

The estimation of the relationship between climate change and electricity use per capita in Africa was based on a modification of the traditional consumption relationship for electricity. The study formulated the relationship to include climate change. This is given as

Ce = f(Upop, Hs, EI, CC)

Where Ce is electricity use per capita.

Upop is the urban population as a percentage of total population.

Hs is the number households.

EI is the energy intensity.

CC is climate change.

Climate change was represented with the cost of climate change to Africa, which is a conservative average 2% of annual Gross Domestic Product for each country (Clements, 2009). Number of Households was computed by dividing total population by 5, the average household size. Energy Intensity was computed as GDP at 2010 constant US$ price divided by total energy use. A summary of the framework for achieving the objectives of the study is provided in Table 1.

Table-1. Framework for Analysis.

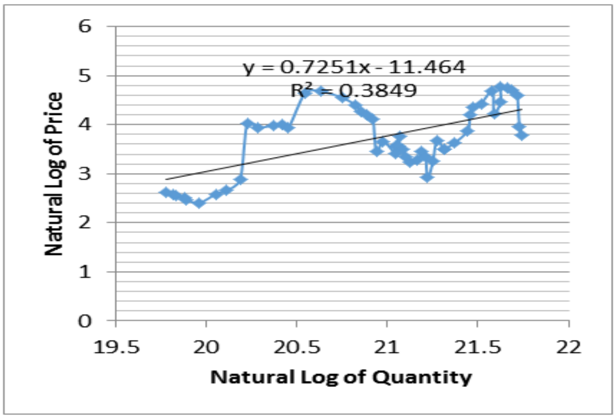
Research Objective	Estimation model	Technique used	Data sources
Trends in marginal costs of fossil fuel and renewable energy available to Africa	MC = dP/dQ(ln P/Q)	Scatter plot, line of best fit	WDI 1960 – 2016 DOE (2012); Frankel, Kane, and Tryggestad (2018)
Backstop resource capable of replacing fossil fuel	$p_t = MC + (p_0 - MC)(1 + r)^t$	Hotelling Rule	WDI 1960 – 2016 Urban and Mitchell (2011)
Determination of switch point between fossil fuel and renewable energy	$p_t = MC + \dfrac{(MC_b - MC)}{(1 + r)^{T-1}}$	Hotelling Rule	WDI 1998 -2014
Climate change as a determinant of electricity availability in Africa	Ce = f(Upop, Hs, EI, CC)	Scenario building, tabulation of effects Multiple regression analysis	World Development Indicators (WDI) 1971 – 2014

Source: Frankel et al. (2018) and Hotelling (1931).

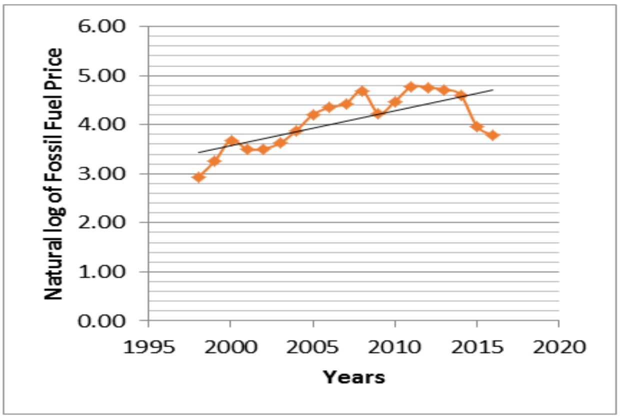
5. RESULTS AND DISCUSSION

5.1. Marginal Costs of Fossil Fuel and Renewable Energy in Africa

A plot of the natural log of fossil fuel prices against quantities used at those prices was constructed from WDI data from 1960 to 2016. The slope of the line of best fit represents the marginal cost of fossil fuel based on the Hotelling Rule. Figure 1A shows this plot with the slope of the line of best fit being 0.73. This means the rate of change of the cost of fossil fuel with respect to a unit increase in the quantity of fossil fuel used in Africa between 1960 and 2016 was about 73%. Following the marginal cost for fossil fuel curve, a trend of the log of fossil fuel prices was plotted against time to show the time trend of the log of fossil fuel prices. The time in this case was found to be highly correlated to the natural log of the quantity of fossil fuel used within the period. Figure 1B shows the plot for the period from 1998 to 2014. The time period was reduced from 1960 to 2016 so that the trend would be compatible with the trend for the natural log of renewable energy prices Figure 2, which began from 1998 to 2014. This was done to make direct comparison of the two trends possible.



(A)



(B)

Figure-1. Marginal cost of fossil fuel used in Africa from 1960 to 2016.

The trend of natural log of fossil fuel prices was found to be upward sloping with respect to time Figure 1B. Following the period from 1960 to 2016 the average rate of increase in marginal cost for this trend was about 73% Figure 1A.

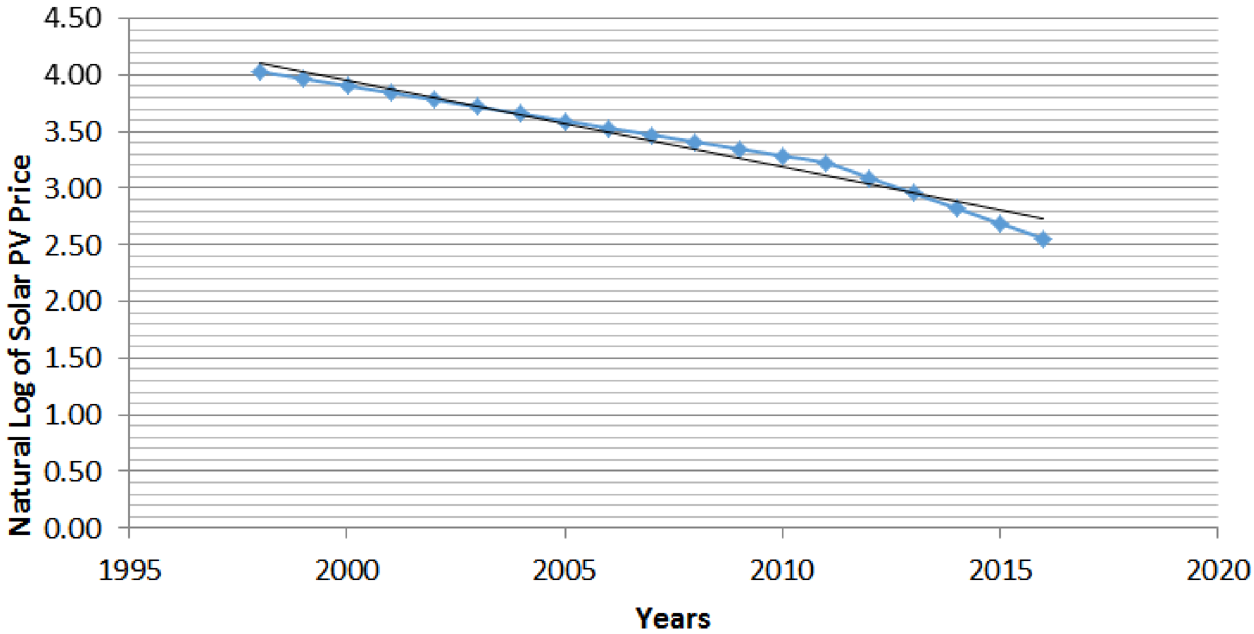


Figure-2. Trend of marginal cost of solar PV.

Source: Author's construct with data from Frankel et al. (2018); IRENA (2014).

Figure 2 shows the trend of the natural log of renewable energy (represented by Solar PV) prices with respect to time. As explained earlier, this trend has been made possible through natural, economic, financial and technological factors. Generally, the rate of change has been an average annual decrease of about 7.6% Figure 2 and beyond a cumulative value of about 80% since 1998 (Frankel et al., 2018; IRENA, 2014).

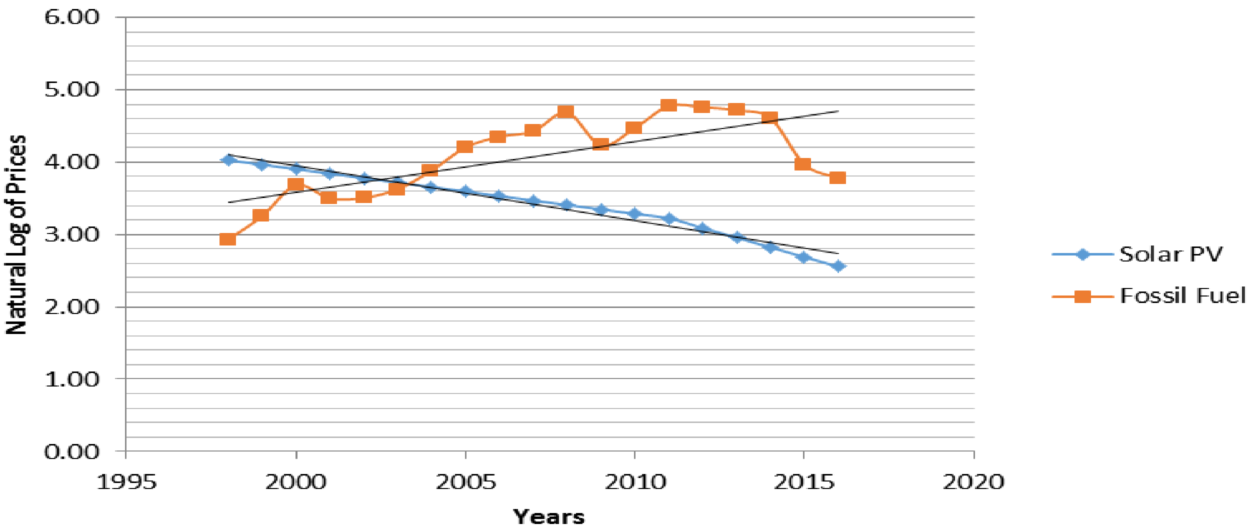


Figure-3. Marginal costs of fossil fuel and solar PV.

Superimposing the marginal cost of fossil fuel curve over the marginal cost of solar photovoltaic curve, we obtain the switch point between fossil fuel and solar PV as well as the marginal cost at which the switch should occur for optimal resource allocation Figure 3.

The mean aggregate rate of change of the marginal cost of solar photovoltaic was a decrease of about 80%. This is against an average increase in private marginal cost of fossil fuel of 73% over the same period. This gives a point of intersection at 2003. It is at this point where the usefulness of a backstop technology resource comes in if available. The fact that a source of energy with infinite supply is available at a decreasing marginal cost makes the case for a shift from fossil fuels to solar PV as the main source of clean energy, based on the Hotelling Rule for optimization of resource allocation. The study thus confirms that Solar PV is a suitable backstop energy source and the switch year should have been 2003 for Africa.

5.2. Climate Change and Electricity Availability in Africa

Table 2 shows the impact of climate change on electricity generation from fossil fuels, hydropower, wind energy, solar energy and biomass. One main constraint which Africa's electricity sector has to operate under is that of extreme inadequate supply of reliable and affordable electricity. Currently, only the electricity generated mainly by the state or its representative can be purchased for use. This makes electricity availability subject to electricity generation by large utility firms.

Table-2. Effects of climate change on various electricity generation sources in Africa.

Change in meteorological variable	Fossil Fuels	Hydropower generation	Wind	Biomass	Solar
Temperature increase	-	-	+/-	-	+/-
Increase in rainfall	none	+	none	+	-
Decrease in rainfall	-	-	none	-	+
Droughts	-	-	none	-	+
Glacier melting	none	none	none	none	None
Floods	-	+	-	-	None
Increased storms/cyclones	-	-	-	-	-
Changes in average wind/solar radiation	-	-	+/-	-	+/-
Environment related uncertainty causing global lockdown (like COVID-19)	-	none	+	none	+

5.3. Scenario Analysis

The signs in Table 2 signify the outcomes of changes in stated meteorological variables on the stated sources of electricity generation. These are mainly effects on power plants and availability of the resource for electricity generation. Once the source is constrained by a given meteorological variable, the effect on electricity generation from that source will be negative (–), since it will generate less or no electricity under tropical African conditions. If on the other hand a meteorological variable enhances the capacity of a stated source of electricity to produce more electricity, then the ultimate outcome for that source will be positive (+), leading to increased generation of electricity. The detailed analysis is provided under the meteorological variable headings following.

5.3.1. Increase in Temperature

The tropical climatic condition of Africa makes it very sensitive to higher temperatures. Increasing temperatures mean a potential drain on water resources for cooling purposes. This will result in decreased fossil fuel based electricity production. Also, higher temperatures decrease the production efficiency of fossil fuel power plants. The cumulative impact of increases in temperature on fossil fuel based electricity production will thus be negative.

For hydropower based electricity production, higher temperatures will result in increased evaporation, reduced river run-off and lower water levels in dams causing decreased electricity generation. This also produces a negative impact on hydroelectricity production.

With respect to wind based electricity production, higher temperatures would result in indirect effects on air density and wind patterns which could either increase or decrease electricity generation. Here the ultimate effect could either be positive where resulting wind density and directions increase electricity generation or negative where wind density and direction create undesirable conditions for wind based electricity production.

Biomass based electricity production will respond to increases in temperature negatively. Here, the impact on water availability for biomass thermal plant cooling would negatively affect electricity generation. Also, reduced availability of biomass could occur if plants reach their threshold of biological heat tolerance or if sea level rise reduces the area where plants grow around coastal areas. Even if there is an increase in biomass availability, there will be an increased fire risk due to high temperatures thereby adversely affecting crop harvests. Increased temperatures decrease the thermal generation efficiency of biomass based power plants. Hence the cumulative effect of increasing temperatures on biomass based electricity production would be negative.

For solar based electricity production, increasing temperatures would generate either positive or negative impacts in Africa. Solar electricity production would be better if temperature increases are accompanied by increased solar radiation and lower cloud cover. Unfavorable conditions would result if higher temperatures are accompanied with decreased solar radiation and higher cloud cover. If temperature increases are not accompanied with changes in solar radiation or cloud cover, then solar electricity production could remain unchanged. However, increased temperatures would decrease the thermal generation efficiency of solar power plants.

5.3.2. Changes in Rainfall

Changes in rainfall volumes and patterns due to climate change are mainly increases which may usually go beyond the normal or decreases far below the normal. For fossil fuel based electricity production, there will be no impact of increase in average rainfall unless the increase results in a flood. However, a decrease in average rainfall will result in decreased availability of water for cooling purposes, which will cause a decrease in electricity generation, a negative effect.

In the case of hydroelectricity, an increase in rainfall will result in increased river run-off and higher water levels in hydro dams, which would lead to increased electricity generation. Hence the ultimate impact will be positive. However, a decrease in average rainfall will reduce river run-off causing lower water levels and therefore decreased electricity generation, a negative effect. With respect to wind based electricity production, changes in average rainfall will have no impact on electricity production.

Biomass-based electricity generation could benefit from higher biomass availability if the increase in rainfall occurs during the growing season. This could result in increased electricity generation. Hence the ultimate effect of increased rainfall will be positive for biomass-based electricity generation. A decrease in average rainfall will however result in lower biomass availability unless rainfall decreased outside the biomass growing season. Thus a decrease in average rainfall would result in a decreased electricity generation, usually accompanied by increased fire risk which jeopardizes crop harvests.

In the case of solar based electricity generation, if increased rainfall is accompanied with decreased solar radiation and more cloud cover, then the effect would be adverse otherwise there would be no effect on electricity production. This means the ultimate effect would be a decreased or unchanged electricity production from solar sources. However, with a decrease in rainfall, which mostly comes with low cloud cover and increased solar radiation there will be an increase in electricity production, which is a positive effect.

5.3.3. Droughts

Droughts generally cause decreased availability of water for cooling purposes and will thus result in decreased electricity production for fossil fuel based electricity generation in Africa. Thus droughts will have a negative effect on fossil fuel based electricity.

Also, due to reduced river run-off and lower water levels brought by droughts there will be decreased electricity generation from hydroelectricity. This will be a negative effect for hydroelectricity. Wind based electricity will not be influenced by droughts.

With respect to biomass-based electricity production, lower biomass availability due to droughts would result in decreased electricity generation accompanied by increased fire risk, which could adversely affect crop harvests. Thus droughts would have a negative effect on biomass-based electricity production.

5.3.4. Floods

Floods in Africa have generally been very devastating for all sectors of the economy, especially energy. With respect to fossil fuel based electricity production, flooding has been one of the dangers to both production and distribution equipment, causing decreased electricity production. The negative effect has been rather extensive due to low capacity of most African infrastructure to withstand flooding.

Glacier melting could result in coastal flooding, creating negative impacts for electricity production. However, if glacier melting does not cause flooding, it will have no effect on any source of electricity generation in Africa.

With respect to hydropower electricity production, increased river run-off and higher water levels could lead to increased electricity generation if grid equipment are not adversely affected by floods. In the case of wind and biomass-based electricity production, the effects of flooding would be negative due to equipment flooding, with biomass-based production suffering further if the resulting flood causes scarcity of needed biomass. Solar electricity generation would however not be affected much in the case where solar systems are mostly stand-alone photovoltaic systems.

5.3.5. Storms and Cyclones

Storms and cyclones have had devastating effects in many parts of the world, especially in developing countries. Energy production under storms and cyclones has suffered negative impacts in Africa particularly, due to lack of climate resilient energy infrastructure. Thus in Africa, storms and cyclones have negative effect on all energy production sources.

5.3.6. Changes in Wind and Solar Radiation

Higher wind and solar radiation would generally have negative effects on electricity production from fossil fuel, biomass and hydropower systems respectively in Africa. In each case the resulting drier conditions would cause decreased electricity production. In the case of wind and solar based electricity production, higher wind and solar radiation would result in increased electricity production, a positive effect. Lower wind and solar radiation would result in decreased electricity production for wind and solar based electricity production. Thus for wind and solar systems, the effect of changes in wind and solar radiation could either be positive or negative for electricity production.

5.3.7. Changes in Global Conditions Leading to Global Lockdown

Based on health protocols aimed at slowing the spread of the COVID-19 pandemic, energy use declined from 5% in March 2020 to 50% in April, 2020. International Energy Agency (IEA) (2020) analysis of daily data through mid-April, 2020 showed that countries that enforced full Covid-19 lockdown measures experienced about 25% decline in energy demand per week while those that enforced partial lockdown had about 18% decline. Thus for the 30 countries studied daily by the IEA until 14th April 2020, which accounted for over two-thirds of the global demand for energy, the duration of a country's lockdown severity and length were the main determinants of reduction in energy demand (International Energy Agency (IEA), 2020).

Within the general first wave of the outbreak, the demand for coal globally decreased by about 8% relative to the first quarter of 2019. The demand for Oil fell by 5%, because of restrictions on air and land transportation, which make up almost 60% of the demand worldwide.

However, renewable energy enjoyed a boost in electricity generation due to the lockdowns and fall in demand for electricity. On the global scale, electricity generation fell by 2.6% in the first quarter of 2020 compared to the first quarter of 2019. Electricity generation from renewable energy sources went up by 3%, based on increased output of wind electricity and solar photovoltaic (PV) responding to the execution of new projects previously approved. The percentage increase in renewable electricity supply was about 28% in the first quarter 2020, from 26% in the first quarter of 2019 (International Energy Agency (IEA), 2020).

The assessment expects renewable energy demand to rise in 2020 due to low costs of operation as well as preferential access to many power systems. Even in the midst of some supply chain disruptions, the International Energy Agency (IEA) (2020) expects growth in solar, wind and hydro projects to raise renewable electricity generation by about 5% in 2020, an increase which is lower than the expectation prior to the Covid-19 pandemic. The production of renewable energy is expected to be neutral to the speed of recovery from the Covid-19. A faster rate of recovery would lead to completion of more renewable energy projects while a slower rate would still lead to an increase as has been the case during the pandemic. Thus, renewable energy sources have become the most resilient energy sources during the Covid-19 pandemic (International Energy Agency (IEA), 2020).

Table 2 presents the results of the effects of changes in meteorological variables on various energy sources. Negative signs depict negative impacts while positive signs depict positive impacts. The energy source that yields the highest number of positive signs is the most resilient to climate change, while the source with the highest number of negatives is the least resilient to climate change. From the table, hydropower and solar sources are the most resilient, while fossil fuels are the least resilient.

The results show that due to climate variability, it makes sense to transit from fossil fuels to renewable energy sources. Thus it will be more costly to rely on fossil fuels for energy relative to renewable sources in the presence of climate change.

6. REGRESSION ANALYSIS

Traditionally, models of energy consumption have not included climate change as a variable. For developing countries which have been the most vulnerable to climate change, most of which are already experiencing negative effects from extreme climate events, this cannot be overlooked. The study therefore run a regression to determine the relationship between climate change and the per capita consumption of energy in Africa as discussed earlier. The regression analysis is a way of ascertaining the dependence of per capita electricity consumption in Africa on climate change, with a view to predicting the value of per capita electricity consumption in terms of known climate change occurrences. This was preceded by initial tests for stationarity of the variables. Table 3 presents results of the unit root test.

Table-3. Unit root test results for regression variables.

Variables	Levels	Test Statistic	Critical Value (5%)	P-value
Ln(Electricity)	Level	-2.781	-3.528	0.204
	First Difference	-4.336	-2.952	0.0004*
Ln(Climate Change)	Level	0.518	-3.528	0.9969
	First Difference	-3.897	-2.952	0.0021*
Ln(Energy Intensity)	Level	0.124	-3.528	0.9953
	First Difference	-4.73	-2.952	0.0001*

Note: * satisfied stationarity condition.

Based on ARDL model requirements, the Dickey Fuller Unit root test was used. Results from Table 3 show that all three variables were non-stationary at their levels. It also shows that, all three variables were stationary at their first difference.

Table-4. Bounds test results.

Tests	Test Statistic	10%		5%		1%	
		Lower	Upper	Lower	Upper	Lower	Upper
F	9.235	3.17	4.14	3.79	4.85	5.15	6.36

The Bounds test was performed to ascertain the existence of a long run relationship among the variables. The Bounds test has a null hypothesis of no levels relationship. Only by rejecting the null hypothesis can one conclude on the existence of a long run relationship. From the results, the test statistic from the F test of 9.235 is higher than both the lower and upper bound critical values of 3.79 and 4.85 respectively at 5 percent level of significance. Based on this result, the null hypothesis of no levels relationship was rejected. It therefore means there exists a long run relation among the variables.

Table-5. ARDL (3 1 0) error correction model, long run and short run model.

D.Ln_Electricity_Con.		Coefficient	Std. Err.	t	P-value
ADJ					
ln_Electricity_Con.	L1.	-0.1350	0.0426	-3.17	0.003
LR					
ln_Climate_Change		2.1343	1.1204	1.91	0.065
ln_Energy_Intensity		-2.4066	1.1591	-2.08	0.045
SR					
Constant		0.8390	0.4851	1.73	0.093
ln_Electricity	LD.	0.1224	0.1350	0.91	0.371
	L2D.	-0.3149	0.1327	-2.37	0.023
ln_Climate Change	D1.	0.5710	0.1752	3.26	0.003

Table 5 reports the Adjusted Coefficient model or error correction model, the long run model as well as the short run model. From Table 5, the error correction model was estimated first with an error correction model coefficient of -0.135 which meets the requirement that the error correction model term should be negative and statistically significant. Also, the speed of adjustment towards long run equilibrium is 13.5 percent annually. That means about 13.5% of the deviation of actual values from the long run equilibrium trend is corrected each year.

The next model reported in Table 5 is the long run model. From the result, estimated long run effect of climate change on electricity consumption was 2.1343 with a p-value of 0.065 > 0.05. Thus at the 5% level of significance, climate change does not have a significant influence on electricity consumption. The estimated long run effect of energy intensity on electricity consumption was -2.4066 with p-value of 0.045 < 0.05. Thus at the 5% level of significance, energy intensity negatively and significantly influences per capita electricity consumption.

Table 5 also reports on the short run results. From the result, the estimated short run effect of climate change on electricity consumption was 0.571 with p-value of 0.003 < 0.05. This effect is statistically significant. This implies that climate change cost has a positive and significant influence on electricity consumption in the short run. Thus given that climate change only significantly influences electricity consumption in the short run, it means climate change has a partial causal effect on per capita electricity consumption at the 5% level of significance. However, at the 10% level of significance climate change has a full causal effect on per capital electricity consumption in the short run and the long run.

The results in both Table 5 and Table 6 confirm the positive and significant relationship between climate change and per capita electricity consumption. Thus, the implication is that, climate change will cause Africa to lack more electricity due to its current dependence on fossil fuel based systems. This will make African economies worse off, since it will require more expenditure to keep up with current energy demand as well as satisfy its growing annual demand for electricity. Such an outcome goes to confirm the results of the scenario building approach used in Table 2. The optimal decision therefore will be for a transition to solar energy which will result in the least challenge for electricity production under climate change than any other source of energy. Hence the least adverse welfare effect of climate change from Africa's electricity sector can only be realized if Africa transits from fossil fuel based electricity production to solar energy based electricity production.

Table-6. Regression results for climate change and electricity use in Africa.

Dependent Var: Electricity Power usage per capita	Coefficient	Standard Error	t	P-value
Constant	-151.882	102.1847	-1.49	0.1450
Urban Population (% of total)	43.54584	9.606923	4.53	0.0000
Number of Households	-4.75E-06	1.99E-06	-2.39	0.0220
Energy Intensity	-6.50E-07	1.82E-07	-3.57	0.0010
Climate Change	4.62E-08	1.03E-08	4.49	0.0000
Number of Observations (Years)				44.0000
F(4, 39)				93.8800
P-value				0.0000
Adj. R^2				0.8963

Table 6 shows the results of the regression, using data from WDI, 1971 to 2014. Since increasing urbanization and population growth have been considered pertinent with respect to Africa's energy requirements, their inclusion in the regression model Table 6 was to verify the extent to which energy consumption per capita would change if they are taken into account.

From the results in Table 6, all the independent variables have significant influence on per capita electricity consumption. While the number of households and energy intensity negatively and significantly affect per capita electricity consumption, urban population and climate change positively affect electricity consumption per capita. The coefficient of determination from the regression was 0.8963 – meaning about 90% of the variation in electricity consumption per capita (the dependent variable) was explained by the model. The study thus rejects the null hypothesis and accepts the research hypothesis that there is a positive and significant relationship between climate change and electricity consumption per capita in Africa. Thus sticking to fossil based electricity systems would worsen Africa's vulnerability due to climate change.

This finding is confirmed by Van Aalst (2006) who found that the effects of climate induced extreme occurrences often got worsened by high levels of deprivation, which eventually hurts the poor more than before.

7. THE WAY FORWARD AND CONCLUSION

The findings show the need for improvement in the way Africa perceives electricity. The perception that centralized and large utility firms are the ones that must provide electricity through fossil fuel-based systems, must give way to a more diverse, participatory and competitive system. Here, consumers are empowered to also produce and control their use of electricity in such a way that maximizes their satisfaction while at the same time maintaining the quality of the natural environment. Specifically, the following steps would lead Africa to get on the transition to reap benefits of the current energy transformation.

7.1. Switching to Solar PV as the Main Source of Electricity

Africa should with immediate effect acknowledge the fact that the risk of failure of its fossil fuel based electrical systems has increased significantly as compared to a situation where its main sources of electricity were renewable, due to climate change. Thus, given the severity of extreme climate events and COVID-19 in recent times, renewable energy sources would be more efficient and resilient than the fossil fuel-based systems Africa is currently dependent on. In addition, given the derived switch point of 2003, Africa has for the past 16 years depended on electrical energy sources which are economically less efficient than the optimal. This implies an inefficient allocation of energy resources.

Also, the readily available nature of renewable energy sources in Africa provides the continent with an opportunity to be self-sufficient in clean energy, reducing the requirement to import large quantities of fossil fuels. Available information confirms the financial burden borne by economies in Africa due to large fossil fuel imports and how this serves as a drag on progress. While Africa needs foreign aid, it is worth noting that in 2010, economies in Africa imported USD 18 billion worth of oil, far in excess of all the aid received in that year (IRENA, 2013).

Therefore, Africa needs to begin preparations for a massive and immediate switch to solar energy to save itself any further unnecessary loss of value and economic welfare. This should have happened in 2003, therefore the earlier it is done the better it will be for the continent, since any further delay will mean a further dissipation of valuable energy resources. While there are some attempts to install some big PV systems in some African countries, these are mainly private efforts and mostly not based on any well designed national or continental plans. The extensiveness of deployment to reach rural households where barely 25% have access to electricity (World Bank, 2015) can generate most needed welfare benefits. Integrated and well planned deployment is what will be sustainable.

7.2. Policy Challenges for an Immediate Switch

The major policy challenge for this way forward will be the plan Africa has concerning the current energy transition. For instance, the ECOWAS Renewable Energy Policy (EREP) targeted a 10% overall renewable energy mix by 2020 and a 19% mix by 2030. Thus if African countries have to go by this target, then the inefficient energy resource allocation will continue even beyond 2030. A poor continent cannot afford to waste resources this way. It is therefore recommended that the EREP target be revised upwards to 30% by 2024 and 70% by 2030. It is worth noting that Cape Verde has a national target of 100% renewable energy sources; as at 2010 it had achieved 25% penetration, heading towards a 50% target by 2020. This is an example of an economy which seeks to run its energy economy efficiently for the realization of optimum welfare for its people.

There appears to have been some will on the part of African countries for a gradual transition based on Africa's Agenda 2063. IRENA (2018) reports that out of 53 African Nationally Determined Contributions (NDCs), 45 contained renewable energy targets. Thus even though this pathway is acknowledged by African countries, because of a lack of awareness of the switch date, it has not been given the attention it deserves to get Africa out of its longstanding electricity problems. Africa no longer has the luxury to remain inefficient; the trade-offs have always been huge and devastating in terms of loss of economic value. Africa is capable of meeting about 25% of its energy needs from indigenous and clean renewable energy by 2030 (IRENA, 2019). Also, accelerated deployment of renewable energy resources in Africa creates jobs, brings health benefits and supports the empowerment of women who represented 35% of renewable energy labor force in 2016 (IRENA, 2016).

In line with the immediate moves to switch, Africa must create a switching investment roadmap to deliver the targets on time. Such a roadmap will also increase the confidence of investors in the switching programme while at the same time accelerating progress. There will be the need to redesign existing energy systems for efficient renewable energy resource delivery. This also means Africa must cease to create new investments in fossil fuel based energy systems. Any new investment must necessarily be based on solar energy systems.

7.3. Internalizing Externalities

Africa must internalize the externalities of fossil fuel use. The use of carbon taxes are recommended here. The exclusion of external costs in the pricing of fossil fuels has been the most important obstacle to Africa's transition to its optimal source of electricity production, as discussed earlier. As long as the price of fossil fuels remain undercut due to externalities, the economic incentives for Africa's optimal energy allocation will remain suppressed (Timmons et al., 2014). While challenges exist for the implementation of carbon taxes, the African situation makes it possible to identify the big polluters for taxation, as a starting point. Even where the poor may have to bear some adverse distributional effects, various systems for identifying and compensating the poor and vulnerable, which have worked well to some extent in some African countries, like Ghana's Livelihood Empowerment Against Poverty programme (LEAP) can be a way out. These could be used to ensure the poor and vulnerable are adequately compensated for any resultant adverse distributional effects of carbon taxation.

7.4. Subsidizing Solar PV

In addition to governments investing in renewable energy systems they should also subsidize renewable energy based projects. This will encourage private sector investment in the sector and also offset past damage caused through the use of fossil fuel, as well as the subsidy provided for fossil fuel. Oil subsidies in Africa cost an estimated USD 50 billion every year, while the investment needed annually to transform Africa's energy sector to renewable sources by 2030 is about USD70 billion (IRENA, 2015). Thus if the resources used to finance fossil fuel subsidies are converted to funding for renewable energy development, there will be enough funding to achieve the set goals.

Badcock and Lenzen (2010) and Timmons et al. (2014) have confirmed the efficacy of subsidies in encouraging an efficient transition to renewable energy in the United States of America. Africa needs to learn from this example of supporting the development of renewable energy through offering subsidies in its favor.

7.5. Research and Funding

Research funding must be provided by African governments as well as private sector institutions for country specific renewable energy system research, with respect to downscaling the transition in individual countries and the involvement of local communities and households. For example, the true nature of demand for electricity must be known and clearly understood, so as to be able to use demand response measures to estimate the quantity demanded of renewable energy, based on optimal resource allocation principles.

7.6. Moving from Pilots to Deployment

For several years, most renewable energy projects in Africa have been pilot projects. Many of them have not been purposefully designed to replace the fossil fuel systems currently dominant on the continent. While it is economically, socially and technically beneficial to devote time, effort and resources to a full-scale transition, Africa appears undecided and satisfied with pilot renewable energy projects.

There is therefore the need for countries to consciously plan to end the dominion of fossil fuels. This must be seen not only through vague documents which never receive budgetary support, but realistic plans which are pursued from beginning to end. Thus, beyond 2020, Africa must concentrate on initial deployment at scale for solar PV technologies that have already been successfully demonstrated. The operationalization of the first demonstration projects for solar energy in Africa is necessary to ensure more certainty about their feasibility and further deployment (Watson et al., 2012).

7.7. Conclusion

Changes in energy consumption patterns in Africa are being influenced by climate change. These changes have the tendency to impose economic and political pressures which will constrain human welfare and economic progress on the continent.

The study finds more than 70 percent increase in the marginal cost of fossil fuel compared to a cumulative reduction of 80 percent in the marginal cost of solar photovoltaic over the study period. Also, the switch point to renewable energy as the main source of clean energy in Africa was found to be 2003. This means Africa's transition to renewable energy as its main source of electricity is overdue by 17 years. For sustainable delivery of energy in Africa, the study recommends policies to internalize the externalities of fossil fuel, backed by recovery subsidies to make up for the loss of welfare from fossil fuel use and to create an enabling environment for a speedy energy transition in Africa's changing climate.

The solutions will require a rapid and complete transition to renewable energy immediately, based on the proposals provided. The speed of the transition will be dependent on policy choices of African nations. African governments can therefore speed up the development of their economies not just by creating the world's largest free trade zone, but more importantly by transiting to renewable energy. Successful execution of steps for the transition will depend on the extent to which incentives will be created for the adoption of the available technologies and innovation through electricity market reform and related government policy initiatives.

Funding: This study received no specific financial support.
Competing Interests: The author declares that there are no conflicts of interests regarding the publication of this paper.
Acknowledgement: The author gratefully acknowledges constructive comments from the 6th Climate Change and Population Conference, 2018 in Accra Ghana, where an earlier version of this paper was presented.

REFERENCES

AfDB. (2016). *Annual development effectiveness review 2016: Accelerating the pace of change.* Abidjan: African Development Bank Group.

Ahlborg, H., Boräng, F., Jagers, S. C., & Söderholm, P. (2015). Provision of electricity to African households: The importance of democracy and institutional quality. *Energy Policy*, *87*, 125-135.Available at: https://doi.org/10.1016/j.enpol.2015.09.002.

Akar, B. G. (2016). The determinants of renewable energy consumption: An empirical analysis for the Balkans. *European Scientific Journal*, *12*(11), 594-607.Available at: https://doi.org/10.19044/esj.2016.v12n11p594.

Badcock, J., & Lenzen, M. (2010). Subsidies for electricity-generating technologies: A review. *Energy Policy 38*, 5038-5504.

Barnett, H. J., & Morse, C. (1963). *Scarcity and growth: The economics of natural resource availability*. Baltimore, MD: Johns Hopkins University Press for Resources for the Future.

BP. (2013). BP statistical review of world energy. Retrieved from: www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html [Accessed on 12th March 2019].

Brennan, W. J., Schulz, P. A., Elwood, J. W., Amthor, J. S., Slimak, M. W., & Laurier, F. J. G. (2008). *Effects of climate change on energy product on and use in the United States*. United States: US Climate Change Science Program.

Brunnschweiler, C. N. (2009). Finance for renewable energy: An empirical analysis of developing and transition economies. Zurich: CER-ETH – Center of Economic Research, Working Paper No. 09/117.

Chari, V. V., & Christiano, L. (2014). The optimal extraction of exhaustible resources. Economic Policy Paper No. 14-5, Federal Reserve Bank of Minneapolis, United States of America.

Choleta. (2015). *Mitigating the wildfire risk to electric utilities*. Edmond, OK: Choleta.

Clements, R. (2009). *The economic cost of climate change in Africa*. Paper presented at the Report for Conference of the Parties 15 in Copenhagen, Denmark: Pan African Climate Justice Alliance.

DOE. (2012). Photovoltaic pricing trends: Historical, recent, and near-term projections. United States Department of Energy. Retrieved from http://www.nrel.gov/docs/fy13osti/56776.pdf.

Erdal, L. (2015). Determinants of energy supply security: An econometric analysis for Turkey. *Ege Academic Review, 15*(2), 153-163.Available at: https://doi.org/10.21121/eab.2015217981.

ESMAP. (2011). *Climate impacts on energy systems. Key issues for energy sector adaptation*. Washington D.C: ESMAP.

Eyraud, L., Wane, A., Zhang, C., & Clements, B. (2011). Who"s going green and why? Trends and determinants of green investment. Working Paper No. 11/296: International Monetary Fund, Washington, D.C.

Frankel, D., Kane, S., & Tryggestad, C. (2018). *The new rules of competition in energy storage*: McKinsey & Company.

Harris, & Roach. (2018). *Environmental and natural resource economics: A contemporary approach*. New York: Taylor and Francis.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy, 39*(2), 137–175.

Intergovernmental Panel on Climate Change (IPCC). (2007a). *IPCC forth assessment report: Climate change 2007: Synthesis report*. Geneva: IPCC.

Intergovernmental Panel on Climate Change (IPCC). (2007b). *Climate change 2007: Impacts, adaptation and vulnerability*. Cambridge: Working Group II. Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2014). Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, Cambridge University Press.

International Energy Agency (IEA). (2007). *Renewables in global energy supply*. Paris: IEA/OECD.

International Energy Agency (IEA). (2020). Global energy review 2020. International Energy Agency. Retrieved from www.iea.org. [Accessed 18th May, 2020].

International Monetary Fund (IMF). (2019). Global fossil fuel subsidies remain large: An update based on country-level estimates. IMF Working Paper No. WP/19/89.

IRENA. (2013). *Africa's renewable energy future. The path to sustainable growth*. Abu Dhabi: IRENA.

IRENA. (2014). *REthinking energy: Towards a new power system*. Abu Dhabi: IRENA.

IRENA. (2015). *Africa 2030: Roadmap for a renewable energy future*. Abu Dhabi: IRENA.

IRENA. (2016). *Investment opportunities in West Africa: Suitability maps for grid-connected and off-grid solar and wind projects*. Abu Dhabi: IRENA.

IRENA. (2018). *Renewable energy in national climate action*. Abu Dhabi: IRENA.

IRENA. (2019). *Scaling up renewable energy deployment in Africa. Overview of IRENA's engagement*. Abu Dhabi: IRENA.

IRENA. (2020). *Renewable power generation costs in 2019*. Abu Dhabi: International Renewable Energy Agency

IRENA. (2020a). *Renewable capacity statistics 2020*. Abu Dhabi: International Renewable Energy Agency.

Jacobson, M. Z., & Delucchi, M. A. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy*, *39*(3), 1154-1169.Available at: https://doi.org/10.1016/j.enpol.2010.11.040.

Jaglom. (2014). Has been corrected to (Jaglom, 2014), which already exists in the references.

Jerez, S., Tobin, I., Vautard, R., Montávez, J. P., López-Romero, J. M., Thais, F., & Déqué, M. (2015). The impact of climate change on photovoltaic power generation in Europe. *Nature Communications*, *6*(1), 1-8.

Jones, D., Graham, E., Tunbridge, P., & Ilas, A. (2020). Global electricity review 2020. EMBER Report.

Kirchner, R., & Salami, A. (2014). Promoting a low cost energy future in Africa. *African Journal of Environmental Science and Technology*, *8*(2), 91-98.Available at: https://doi.org/10.5897/ajest2013.1619.

Lee, J., List, J. A., & Strazicich, M. C. (2006). Non-renewable resource prices: Deterministic or stochastic trends? *Journal of Environmental Economics and Management*, *51*(3), 354-370.Available at: https://doi.org/10.1016/j.jeem.2005.09.005.

Livernois, J. (2008). On the empirical significance of the hotelling rule. *Review of Environmental Economics and Policy*, *3*(1), 22-41.

Lokonon, B. O. K., & Salami, A. O. (2017). Climate change and renewable energy generation in Africa. Working Paper Series N° 269, African Development Bank, Abidjan, Côte d'Ivoire.

Moazzami, B., & Anderson, F. (1994). Modelling natural resource scarcity using the'error-correction'approach. *Canadian Journal of Economics*, *27*(4), 801-812.Available at: https://doi.org/10.2307/136184.

Ogden, J. M., Williams, R. H., & Larson, E. D. (2004). Societal lifecycle costs of cars with alternative fuels/engines. *Energy Policy*, *32*(1), 7-27.Available at: https://doi.org/10.1016/s0301-4215(02)00246-x.

Owen, A. D. (2006). Renewable energy: Externality costs as market barriers. *Energy Policy*, *34*(5), 632-642.Available at: https://doi.org/10.1016/j.enpol.2005.11.017.

Pašičko, R., Branković, Č., & Šimić, Z. (2012). Assessment of climate change impacts on energy generation from renewable sources in Croatia. *Renewable Energy*, *46*, 224-231.Available at: https://doi.org/10.1016/j.renene.2012.03.029.

Pohl, B., & Mulder, P. (2013). Explaining the diffusion of renewable energy technology in developing countries. Working Paper No. 217, Hamburg: German Institute of Global and Area Studies (GIGA).

Reed, D. A., Powell, M. D., & Westerman, J. M. (2010). Energy infrastructure damage analysis for hurricane Rita. *Natural Hazards Review*, *11*(3), 102-109.Available at: https://doi.org/10.1061/(asce)nh.1527-6996.0000012.

Slade, M. E. (1982). Trends in natural-resource commodity prices: An analysis of the time domain. *Journal of Environmental Economics and Management*, *9*(2), 122-137.

Smith, V. K. (1979). Natural resource scarcity: A statistical analysis. *The Review of Economics and Statistics*, *61*(3), 423-427.

Svedberg, P., & Tilton, J. E. (2006). The real, real price of nonrenewable resources: Copper 1870–2000. *World Development*, *34*(3), 501-519.

Tietenberg, T., & Lewis, L. (2012). *Environmental and natural resource economics*. Boston: Pearson Education, Inc.

Timmons, D., Harris, J. M., & Roach, B. (2014). *The economics of renewable energy*. Medford: Global Development and Environmental Institute.

UNIDO. (2009). Scaling up renewable energy in Africa. 12th Ordinary Session of Heads of State and Governments of the African Union, Vienna: United Nations Industrial Development Organization.

Urban, F., & Mitchell, T. (2011). Climate change, disasters and electricity generation. Strengthening Climate Resilience Discussion Paper No. 8. Institute of Development Studies at the University of Sussex, Brighton, UK.

Urban, F., & Mitchell, T. (2011). *Climate change, disasters and electricity generation, strengthening climate resilience discussion paper 8*. Brighton, UK: Institute of Development Studies at the University of Sussex.

Van Aalst, M. K. (2006). The impacts of climate change on the risk of natural disasters. *Disasters*, *30*(1), 5−18.

Watson, J., Byrne, R., Morgan Jones, M., Tsang, F., Opazo, J., Fry, C., & Castle-Clarke, C. (2012). *What are the major barriers to increased use of modern energy services among the world's poorest people and are interventions to overcome these effective? CEE Review 11-004*. London: DFID.

Whitley, S., Chen, H., Doukas, A., Gencsu, I., Gerasimchuk, I., Touchette, Y., & Warrall, L. (2018). *G7 fossil fuel subsidy scorecard. Tracking the phase-out of fiscal support and public finance for oil, gas and coal. Policy brief.* London: Overseas Development Institute.

World Bank. (2015). *World bank group support to electricity access, FY2000–FY2014. An independent evaluation.* Washington DC: World Bank Group.

World Bank. (2017). *Linking up: Public – private partnership in power transmission in Africa.* Washington DC: The World Bank.

World Bank. (2018). *The turning of the tide? Global economic prospects, June 2018.* Washington DC: The World Bank.

Wu, G., Deshmukh, R., Ndhlukula, K., Radojicic, T., & Reilly, J. (2015). Renewable energy zones for the Africa clean energy corridor. *International Renewable Energy Agency and Lawrence Berkeley National Laboratory*, 187271.