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Energy and economic factors affecting carbon dioxide emissions in Sudan: An empirical econometric analysis (1969-2015)

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Abstract. The objective of this study is to investigate some energy and economic growth factors in explaining the behaviour of CO_2 emissions in Sudan over the period 1969-2015 using annual time series data. The OLS estimated model shows that there is significant effect of total energy use per capita, oil consumption, GDP per capita GDPP, trade openness and foreign direct investment on CO_2 emissions in Sudan. The estimated model indicates a positively signed and statistically significant coefficient of relationship between the squared GDP per capita and CO_2 emissions in Sudan, thus contradicting the EKC hypothesis claim. The Johansen cointegration test results show existence of a long run equilibrium relationship between CO_2 emissions, energy use and economic growth factors. Consistent with the OLS estimates, the ARDL model results show nonexistence of an EKC as well as showing that energy use per capita and oil consumption as the main deriving factors behind CO_2 emissions in Sudan in both the short run and long run. The ARDL model also indicates that CO_2 emissions adjust to a steady state equilibrium position by a factor of 66%. Granger causality test shows existence of bidirectional relationship running from GDPP value and the squared GDPP to CO_2 emissions with no sign of feedback effects. Oil and FDI are found to be Granger causing CO_2 emissions, indicating pollution haven. The study recommends that energy efficiency measures in terms of proper pricing of oil derivatives, expansion of production and use of liquefied petroleum gas (LPG) and restrictions in production and use of fuel woods and charcoal with sustainability pricing of these forest products should be adopted within the country intended nationally determined contribution. These measures are needed because it is unlikely for a low income country like Sudan to reduce energy use per capita which is already low and energy use per unit of output needed for foresting economic growth. Impacts of FDI need to be assessed and environmentally regulated.
Keywords. Energy use, GDP Per Capita, trade openness, CO_2 emissions, Cointegration, ARDL, Granger Causality, Sudan.
JEL. C13 C32 Q43 Q56.

1. Introduction

Since the early 1990s of the past century perhaps no single environment – development problem has been occupying the international agenda than the problem of global warming caused by greenhouse gas (GHG) emissions chief among them being carbon dioxide CO_2. The Intergovernmental Panel on Climate Change (IPCC) has stated that the most significant environmental problem over the last 50 years is that of global warming due to anthropogenic greenhouse gas emissions (IPCC, 2007 and IPCC, 2007a). In 1997 the world nations have singed Kyoto Protocol (KP) as a framework to stabilize GHG emissions in the atmosphere. Since then, countries have been engaged in different policy initiatives to cutback or slow their CO_2 emissions as identified to be the main cause of the anthropogenic enhanced GHG effect and associated climatic changes. In line with

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the international concern, a huge literature have been emerging as to what development factors that cause and affect GHG emissions at the global, regional and national level. Studies in the early nineties focused on determining a level of economic growth in terms of per capita income at which emissions of CO_2 starts a reverting direction (i.e. from upward slopping to downward slopping over time) in the context of the environmental Kuznets curve (EKC) hypothesis (Grossman & Krueger, 1993; 1995; Seldon & Song, 1994; Shafik, 1994; Holtz-Eakin, & Selden, 1995). The outcome of those early literatures gave little hope for economic growth to resolve such global environmental problem it creates particularly in low income countries. CO_2 emissions per head have been found to strongly correlate with GDP per head across time and countries (Stern, 2011). Rather, the focus has shifted to probe on the major determinants of CO_2 emissions so as to design environmental policies compatible with economic growth objectives throughout the world. The energy sector in particular has been given great emphasis due to the role energy plays in economic growth and importantly as a major source of GHG emissions.

Sudan is lower-middle income country with total GDP estimated at current US$ 12,408 billion in 1990, increased to US$ 97,156 billion in 2015, and GDP per capita of US$ 481 in 1990 increased to US$ 2414 in 2015. The country is a non-annex 1 party although it signed and ratified the KP and yet the government could take voluntary measures to control GHG emissions. Recently, Sudan has signed but has not ratified the Paris Agreement (UNFCC, 2017). However, adaptation measures are extremely important since Sudan is vulnerable to different impacts of climate change including drought, increased temperature, flooding, reduced water supply and even hydropower potential in the long run (USAID, 2017). Such vulnerabilities will further be aggravated by conflict particularly over natural resources including water as in the context of Collier & Hoeftler, (2002) and Stern, (2011). Nonetheless, for effective climate change adaptation and carbon mitigation measures the driving forces of CO_2 emissions in Sudan need to be identified and their relative importance needs to be well understood. In terms of carbon intensity defined as GHG emissions relative to GDP Sudan's GHG emissions increased 41% from 1990 to 2010, averaging 2.5% annually while GDP increased 225% in the same period, averaging 5.8% annually. Despite GDP growing much faster than GHG emissions, in 2011, Sudan's GHG emissions relative to GDP were almost 9 times the world average, indicating significant potential for reductions (USAID, 2017). But both potential adaptation and mitigation measures for Sudan would not be realized unless the main factors of energy and economic growth deriving GHG emissions are well understood.

2. Research problem

In Sudan, direct CO_2 emissions form fuel combustion and commercial energy has been relatively low. Thus, CO_2 emissions in Sudan are mostly composed of methane CH_4 and nitrous oxide N_2O mainly from agriculture, deforestation and energy use, with negligible contribution from the industrial sector. Commercial energy in terms of oil production and consumption has been steadily increasing since the mid 1990s and contributing increasingly to CO_2 emissions. These stylized facts might give an impression that factors leading to increase in GHG generally and CO_2 emissions in particular are mainly energy, land use and land use change based. As, such analysis of relative contribution of energy and economic growth factors would have implications on policies directed toward GHG emissions and climate change policy action in Sudan. This is what is thought to be addressed in this study.

3. Literature Review

In international bodies and authorities concerned with global warming such as the United Nation Framework Convention on Climate Change (UNFCCC), the IPCC and the United States Environmental Protection Agency (USEPA), GHG emissions are classified globally, by region, sub-region and by country. The major GHG is CO_2 and other GHG emissions manly CH_4 and N_2O are usually converted to their CO_2 equivalence. Yet, the World Bank defines CO_2 emissions as those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring. Index Mundi defines CO_2 as those stemming from liquid fuel consumption referring mainly to emissions from use of natural gas as an energy source. World Bank source of data are the World Bank World Development Indicators and CIA Factbook while Index Mundi source of data come from Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States (Index Mundi, 2016). A fact is that, the most advanced regions and countries of the world are the major emitters of GHGs. The top 10 emitters in 2010 were China, the United State of America, the European Union (27 countries), India, Russia, Japan, Germany, Iran, South Korea, and Canada (EPA, 2013). Thus, large scale and high economic growth rate is associated with high emissions of GHGs but also with high level of per capita energy consumption. Yet, the direction of causality between energy consumption and economic growth has not well established. While King & Levine (1993a, 1993b), Neusser & Kugler (1998), Darrat (1999), Levine, Loayza & Beck (2000), Fase & Abma (2003), Christtopoulos & Tsionas (2004), Chang & Caudill (2005), Apergis & Payne (2010 and 2011), Ozturk & Acaravci (2013), Ouedraogo (2013) and Aslan *et al.,* (2014) find that energy consumption leads to economic growth, Jung (1986), Lucas (1988), Chang & Caudill (2006), Huang *et al.,* (2008), Narayan *et al.,* (2010), find that economic growth influences energy consumption, mostly on their search for a role of financial development on economic growth.

For policy intervention at the economic sector level, GHG emissions are broken down by the economic activities that lead to their production. According to EPA, 2013 the major economic activities leading to GHG emissions at the global level were classified into seven groups ranging from energy supply to waste and wastewater. Energy supply has been defined to include burning of coal, natural gas, and oil for electricity and heat as well as emissions from electricity use and as the largest single source of global GHG emissions accounted for 24% in 2004. Industry accounted for 19% of global GHG emissions in 2004 and emissions mainly come from fossil fuels burned on-site at facilities for energy and also include emissions from chemical, metallurgical, and mineral transformation processes not associated with energy consumption. Land use, land-use change, and forestry accounted for 17% of 2004 global GHG emissions where emissions stem from deforestation, land clearing for agriculture, and fires or decay of peat soils. This estimate does not include the CO_2 that ecosystems remove from the atmosphere. The amount of CO_2 that is removed is subject to large uncertainty, although recent estimates indicate that on a global scale, ecosystems on land remove about twice as much CO_2 as is lost by deforestation. Agriculture accounted 14% of 2004 GHG emissions with emissions mostly come from the management of agricultural soils, livestock, rice production, and biomass burning. Transportation accounted for 13% of 2004 global GHG emissions with emissions primarily involve fossil fuels burned for road, rail, air, and marine transportation. EPA noted that almost all (95%) of the world's transportation energy comes from petroleum-based fuels, largely gasoline and diesel. Commercial and residential buildings accounted for 8% of 2004 global GHG emissions arising from on-site energy generation and burning fuels for heat in buildings or cooking in homes. Note that emissions from electricity use are excluded and are instead included in the energy supply sector. Waste and wastewater accounted for 3% of 2004 global GHG emissions where the largest source emissions in this sector is landfill methane (CH_4), followed by wastewater methane (CH_4) and nitrous oxide (N_2O). Incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles, also results in minor emissions of CO_2. From this classification and documentation of sector-based contributions, the most influential factors on the historical GHG emissions can be identified and examined using econometric techniques with time series data in order to assess their relative importance for the purpose of climate policy interventions at the country level.

In empirical literature, economic development factors affecting CO_2 emissions also include capital accumulation, labour, trade, urbanization and the contribution of the services sector to output which cater for structural shift in the economy from energy intensive and highly polluting sectors to a relatively low energy intensive and less polluting sectors. Literature on the determinants of GHG emissions in general and CO_2 emissions in particular at the global, regional and national levels are empirical in nature mostly based on the science of climate change. In economics, studies use the EKC hypothesis with various dynamic econometric techniques. Studies commonly treat CO_2 emissions as the dependent or endogenous variable explained by a set of economic development indictors. The most common explanatory variables affecting CO_2 emissions identified in the literature include gross domestic product (GDP); GDP per capita (GDPP); energy use and energy intensity; trade openness; imports; foreign direct investment (FDI); land use and land use change with deforestation and forestation; agricultural practices and management; household energy consumption; industrial and manufacturing sector share in GDP; urbanization and population growth. At least three indentified determinants of CO_2 emissions have been found included and common in every single empirical study whether at the global, regional, group, or national levels. Technological changes have been identified and found to play important role on reducing CO_2 emission when defined in terms of fuel mix effect and emission coefficient (Wang, Zhang & Yin, 2012). Population density which is important factor in energy distribution and use buy households and commercial buildings have also been identified as determinants of CO_2 emissions.

Friedl & Getzner (2003) explore the relationship between economic development and CO_2 emissions for Austria over the period 1960-1999 in a test for an EKC relationship. They found a cubic (i.e. N-shaped) relationship between GDP and CO_2 emissions, with a structural break in the mid-seventies attributed to the oil price shock. Other two variables found to be significant were import shares reflecting the well-known pollution haven and the share of the service sector in GDP (see also Kearsley, & Riddel, 2010) for further explanation of the pollution haven hypothesis. With emission projections derived from Austria the authors argue for significant policy changes when implementing the KP in order to bring about a downturn in future carbon emissions. Soytas, Sari & Ewing (2007) investigate Granger causality relationship between income, energy consumption and carbon emissions in the US, with inclusion of labour and gross fixed capital formation in their model. They find that income does not Granger cause carbon emissions in the US in the long run, but energy use does, pointing out that income growth by itself may not become a solution to environmental problems as in the sense of the EKC hypothesis. Kerklof, Benders & Moll (2009) identify some determinants of national household CO_2 emissions and their distribution across income groups in the Netherlands, UK, Sweden and Norway. They quantify the CO_2 emissions of households in these countries around the year 2000 by combining a hybrid approach of process analysis and input–output analysis with data on household expenditures. Their results show that average households in the Netherlands and the UK give rise to higher amounts of CO_2 emissions than households in Sweden and Norway and that CO_2 emission intensities of household consumption decrease with increasing income in the Netherlands and the UK, whereas they increase in Sweden and Norway. A comparison of the national results at the product level points out that country characteristics, like energy supply, population density and the availability of district heating, influence variation in household CO_2 emissions between and within countries.

Omri (2009) examines the nexus between CO_2 emissions, energy consumption and economic growth using simultaneous-equations models with panel data of 14 Middle East and North Africa (MENA) countries over the period 1990–2011. The study shows existence of a bidirectional causal relationship between energy consumption and economic growth and existence of unidirectional causality from energy consumption to CO_2 emissions without any feedback effects, as well as a bidirectional causal relationship between economic growth and CO_2 emissions for the MENA region as a whole. Using the bounds test and Granger causality test approaches, Halicioglu (2009) finds that income is the most significant variable in explaining the carbon emissions in Turkey, followed by energy consumption and foreign trade. Iwata & Sovannroeun (2009) find evidence supporting the EKC hypothesis for the case of France showing that the impact of nuclear energy on CO_2 emissions is significantly negative in both the short-run and long-run, but not trade. Energy consumption impact on CO_2 emissions is found to be statistical significance only in the short-run. They find unidirectional causality relationship running from income to CO_2 emissions meaning that economic growth causes more CO_2 emissions, pointing out that any effort to reduce them does not restrain the development of the economy. They also find unidirectional causality relationship running from nuclear energy to CO_2 emissions. Iwata & Sovannroeun (2010) empirically investigate the EKC for CO_2 emissions in 11 OECD countries using the autoregressive distributed lag (ARDL) find that energy consumption has a positive impact on CO_2 emissions in most countries with no statistically significant trade effect. Their results provide evidence for a role of nuclear power in reducing CO_2 emissions only in some countries. Additionally, although the estimated long-run coefficients of income and its square satisfy the EKC hypothesis in Finland, Japan, Korea and Spain, they pointed out that only Finland's EKC turning point is found to be inside the sample period of the study. Zhang & Cheng (2009) investigate Granger causality between economic growth, energy consumption, and carbon emissions in China, applying a multivariate model of economic growth, energy use, carbon emissions, capital and urban population over the period 1960–2007. They find a unidirectional Granger causality running from GDP to energy consumption, and a unidirectional Granger causality running from energy consumption to carbon emissions in the long run. They document that neither carbon emissions nor energy consumption leads economic growth and that the government of China can purse conservative energy policy and carbon emissions reduction policy in the long run without impeding economic growth.

Sharma (2011) investigates the determinants of CO_2 emissions using a dynamic panel data model containing 69 counties divided into sub-panels of high income, middle income and low income panels for the period 1985-2005. The findings were that trade openness, per capita GDP, and energy consumption, defined as per capita electric power consumption and per capita total primary energy consumption have positive effects on CO_2 emissions, while urbanization is found to have a negative impact on CO_2 emissions. For the global panel, only GDP per capita and per capita total primary energy consumption were found to be statistically significant determinants of CO_2 emissions, while urbanization, trade openness, and per capita electric power consumption have negative effects on the CO_2 emissions. Prashanta & Rahman (2012) study the interaction between CO_2 emissions, industrial output growth, population growth and FDI inflows in Bangladesh for the period 1972–2008 using ARDL method and Vector Error Correction Model (VECM) finding evidence of a converging long–run equilibrium relationship between the variables with a long–run causal relationship running from industrial output growth, population growth and FDI to CO_2 emissions, with FDI seems to marginally mitigate CO_2 emissions with a short–run interactive net positive feedback effects among the variables. Wang, Zhang, & Yin (2012) investigate the adaptive implications for energy-intensive industries of China, analyzing the change of CO_2 emissions for 6 energy-intensive sectors over the period of 2000–2007 using a Log-Mean Divisia Index based on time series. They show that there was 146.1 million metric tons carbon increase in energy-intensive industries, with the excessive growth of industrial output and increasingly fossil-intensive energy consumption structure as the main driving forces for the increased CO_2 emission. Nevertheless, energy intensity change and declining emissions coefficient of electricity played negative role in the growing trend of CO_2 emissions. On the basis of industrial output, energy intensity, fuel mix effect, and emission coefficient, it was suggested that both economic motives and technologically feasible approaches should be implemented to control the scale of excessive productions and improve energy efficiency toward the energy-intensive industries as well as strengthening energy-intensive sectors' awareness of climate change adaptation. Camarero, Picaza-Tadeo, & Tamarit (2013) study convergence in CO_2 emission intensity defined as CO_2 emissions over GDP among 22 OECD countries over the period 1960-2008 using energy intensity defined as energy consumption over GDP and the carbonization index defined as CO_2 emissions over energy consumption as determining factors. Applying the Phillips & Sul (2007) methodology in testing for the existence of convergence clubs, their results highlight that differences in emissions intensity convergence are more determined by differences in convergence of the carbonization index rather than by differences in the dynamic convergence of energy intensity. Bento (2014) uses trade openness and energy consumption to explain CO_2 emissions in Italy for the period 1960-2012 applying Granger causality and conintegration methods finding that economic growth is the main driver of CO_2 emissions in the short run, and that Granger causality runs from emissions to economic growth and energy consumption with no evidence of reverse causality.

Direct CO_2 emissions in Sudan are negligible by international levels, particularly from gaseous fuel consumption. According to Index Mundi in 2009, from a total of 197 countries, Qatar ranked number one with an amount of 44.97 CO_2 emissions (metric ton Mt per capita) followed by Trinidad and Tobago as number 2 with an amount of 36.13 (Mt per capita) and Kuwait as number 3 with an amount of 28.12 (Mt per capita). Sudan ranked number 152 with an amount of CO_2 emissions of 0.32 Mt per capita. However, such estimates need to be understood with caution as they are sensitive to population numbers. Other GHG emissions that contribute to CO_2 emissions include Methane CH_4 and Nitrous Oxide N_2O emissions which are relatively high in Sudan. This is mainly due to fact that agriculture has been historically the dominant productive sector of the economy with the industrial and manufacturing industry contributing the least to GDP. CH_4 emissions are those stemming from human activities such as agriculture and from industrial methane production. According to the United Nations Climate Change Secretariat UNCCS of the UNFCCC (2014) agricultural CH_4 emissions are emissions from animals, animal waste, rice production, agricultural waste burning (non-energy, on-site), and savannah burning. Sudan CH_4 emissions in 1970 were 31752 kt of CO_2 equivalent, increased to 64406.4 kt of CO_2 equivalent in 2000, peaked up to 125045 kt of CO_2 equivalent in 2007 but declined to 96531.5 kt of CO_2 equivalent in 2012. In 2010 Sudan was ranked number 15 of a total of 134 countries (World Bank, 2013) with CH_4 missions of 94638.70 kt CO_2 equivalent. Energy related CH_4 emissions were 12.02% of total in 1970, declined to 10.38% in 1980 and to 10.34% in 2000 and further to 6.40% in 2008. Total CH_4 emissions in the energy sector were 3817.81 thousand Mt of CO_2 equivalent, increased to 6661.34 in 2000, but declined to 6449.54 thousand Mt of CO_2 equivalent in 2008 (WB, WDIs, 2017).

Deforestation is a major environmental problem in Sudan with major contributions to GHG emissions. Between 1990 and 2000 deforestation was about 0.77% per annum, increased to 0.84% between 2000 and 2005 and Sudan lost 1,767.000 ha of its primary forest cover during that time. In 2000, total forest area was estimated at 28.4% amount to 67,546.000 hectares declined to 8% by 2015. Of this amount 20.0% or roughly 13,509.000 ha (5.7% of land area) was classified as primary forest. Measuring the total rate of habitat conversion (defined as change in forest area plus change in woodland area minus net plantation expansion) Sudan lost 11.6% or around 8,8858.000 ha of its forest and woodland habitat over the period 1990-2005 (FAO, 2007). According to the FAO, 2007, the pattern of forest use was dominated by production accounting for 44.9%, followed by none or unknown use, 39.9%, conservation accounting for 12.7% and protection accounting only for 2.6%. An important characteristic is that 97.7% of forests in Sudan are public and 2.3% are private which makes forest management quite difficult with limited government resources and control over remote rural areas. By 2015, Sudan total forest area as percentage of total land year was estimated below 10%. Deforestation in Sudan contributes to CO_2 emissions in a dynamic and complex way and one way to model it is through total energy use per capita which is mainly composed of forest products such as charcoal production and burning of wood as a primary energy source as well as indirectly as forests are known to be the major natural sink for carbon emissions. Development in Sudan can also be explained within the context of the frontier expansion hypothesis of Barbier (2007), as from data on Sudan and other countries where agricultural land area is conversely related to forest land area indicating a frontier expansion for development. For example, Suriname has the highest forest land area of 96.58 per cent but the lowest agricultural land area of 0.53 as per cent of total land area. In terms of agricultural land as percentage of land area Sudan ranked as number 47 in 2012 of totally 205 countries. Burundi ranked number one with 86.45, followed by Nigeria with 83.67, Comoros with 83.29 in 2011. Thus, converting forest land to agriculture land is major cause of deforestation and meanwhile contributes to GHG emissions but also removal through different agricultural practices and management, since the mitigation potential from these land based activities is derived from both an enhancement of removals of GHG, as well as reduction of emissions through management of land and livestock (Smith, 2014).

According to the World Resources Institute Climate Analysis Indicators Tool (WRI CAIT), quoted in the USAID, 2017, Sudan's 2011 GHG profile was dominated by emissions from land use change and forestry (LUCF), which accounted for 63.1% of the country's total emissions. Within the LUCF sector, burning biomass accounted for 82% of emissions. Agriculture was the second highest emitter (26.1%) with enteric fermentation from livestock and manure left on pasture contributing 72% of sector emissions. Energy was the third largest source (9.9%), followed by industrial processes (0.5%) and waste (0.4%).

4. Methodology and model specifications

4.1. Definition of concepts and variables

This study is empirical as it seeks to identify the main energy and economic growth factors driving CO_2 emissions in Sudan over the period 1969-2015. In this study CO_2 emissions per capita is defined as the total CO_2 emissions measured in thousand Mt per year divided by the total number of population in that year. Total CO_2 emissions include direct CO_2 emissions, Nitrous Oxide N_2O and Methane CH_4 emissions as the latter two are measured in (000 Mt of CO_2 Equivalent). CH_4 emissions are methane emissions from energy processes are emissions from the production, handling, transmission, and combustion of fossil fuels and bio-fuels. Agriculture is also a major source of N_2O emissions. Agricultural N_2O emissions are emissions produced through fertilizer use (synthetic and animal manure), animal waste management, agricultural waste burning (non-energy, on-site), and savannah burning. N_2O is also emitted in energy processes by the combustion of fossil fuels and bio-fuels. Industrial N_2O are emissions are emissions produced during the manufacturing of adipic acid and nitric acid. Emissions of CH_4 and N_2O build indirectly into total and per capita CO_2 emissions in Sudan.

In the econometric explanatory model built, CO_2 per capita represents the dependent variable, measured in Mt. The explanatory variables included in this study are economic growth and growth related factors represented by GDP per capita, (GDPP) agricultural land area (AL), industrial output (IND) as percentage of GDP, trade openness (TOP) and foreign direct investment (FDI). Both TOP and FDI are included to take care of the international factors that could contribute to CO_2 emissions in Sudan. Energy factors are represented by oil consumption per capita (OIL) and total energy use per capita (EUP). GDPP stands for gross domestic product per capita calculated as the total market value of GDP in a year divided by the total number of population in that year, and it expected to have a positive role on CO_2 emissions as documented in many studies around the world. AL stands for agricultural land area as percentage of total land area. AL could have positive or negative role on CO_2 emissions given agricultural practices and interaction with other land based activities. Expansion in agricultural land in all cases has been and will be expected to be the major source of indirect CO_2 emissions in Sudan through emissions of CH_4 and N_2O as these trace gases indirectly contribute to the calculated final CO_2 emissions per capita. Agricultural GDP (AGP) could also be thought of as a factor contributing to CO_2 emissions which is also expected to be a major potential determinant of CO_2 emissions in Sudan. While AL could be included to cater for land use change and land management, AGP can be thought of to take care of non-land based CO_2 emissions related to agricultural practices. Agriculture and agricultural practices, together with deforestation are important factors in GHG emissions as well as removal and influx meanwhile, particularly in developing countries. Detailed discussions on carbon flux related to land use change can be found in Houghton (2003; 2008), Houghton, & Hackler (1995; 2001); and Smith *et al.,* (2014). FL stands for forest area measured in square kilometers and calculated as the total forest total area divided by total land area. This measure indirectly stands for the level and rate of deforestation that has been taking place in Sudan with an average of 0.84% over the past four decades. It is well established that deforestation is a major source of GHG emissions directly through clearance of forests for different economic activities, charcoal production and burning of wood as a primary energy source as well as indirectly as forests are known to be the major natural sink for carbon emissions. It is of importance to acknowledge that the major energy sources in Sudan have historically been charcoal and fuel wood which account of more than 80% of total energy consumption in Sudan up to the year 2005 and remains almost the same as up to 2015. Commercial energy sources in terms of oil and electricity account for only about 17 percent in the energy balance of Sudan and mostly consumed in urban and semi urban areas. The majority of Sudan population live in rural areas with direct dependency on fuel woods and charcoal as energy sources for different cooking, heating and cooling activities. IND stands for industrial output calculated as the total market value of industrial output in a year divided by GDP in that year. But since the contribution of the industrial sector is lowest compared with the services and agricultural sectors, it is excluded as a factor affecting CO_2 emissions in Sudan. But still can be used a control variable in checking for effect of any omitted variables in the estimated models. TOP stands for trade openness per capita which is measured as the value of exports and imports in a year divided by the GDP. Also included in the study is the value of imports per capita. FDI stands for net flows of foreign direct investments to Sudan.

Oil is conventional energy source. OIL stands for oil consumption per capita measured in barrel of oil per year and calculated as the total oil consumption in a year divided by the total number of population in that year. Note that Sudan was a pure oil and petroleum products importer up to 1998. Since 1999 Sudan started to be a pure oil exporter up until the secession of South Sudan in 2011. As a result oil consumption increased from 0.000386 barrel of oil per capita in 1990 to 0.023464 in 1999, but declined to 0.00083 barrel of oil per capita in 2011 and about 0.02634 in 2015. Up to 1999 the bulk of Sudan imports had been oil and petroleum products. After 1999, although the value of oil imports started to decline but oil consumption has been increasing with increase in the value of other imports. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. In this study EU stands for energy use per capita measured in kilogram of oil equivalent (kgOE) and calculated as the total energy use in a year divided by the total number of population in that year. EU was estimated at 410 kilogram of oil equivalent (kgOE) in 1990 increased to 412 kgOE in 1999 and reached 638 kgOE in 2011 and stands at 814 by the end of 2015. Sudan's final energy consumption in 1983 totalled 6.1 million tons of oil equivalent (TOE), of which 82 percent was fuel-woods, charcoal, and other biomass. The remainder (18 percent) was imported oil and hydroelectricity. Households consumed the largest percentage of fuel (77.8 percent), followed by transport (11.0 percent) and industry (5.8 percent). In 1983 almost all commercial energy in Sudan came from hydroelectricity and imported oil where petroleum imports accounted for 94.5 percent of commercial energy consumption and hydroelectricity supplied 5.5 percent) (UNDP/World Bank, 1983a). The major change since 1995 has been the locally produced and refined oil which adds to increasing amounts of CO_2 emissions. Data on the variables for the purpose of this study is taken from the World Bank, World Development Indicators as updated on May. 2017.

The study uses the conventional descriptive and inferential statistics and econometrics methods, including Johansen cointegration, an error correction model (ECM) of ARDL model and Granger causality analysis, in order to investigate the selected energy and economic growth factors affecting per capita CO_2 emissions in Sudan using annual time series data for the period 1969-2015.

4.2. Descriptive statistical analysis

Descriptive statistical analysis is carried out on actual values of the study variables. Table (1) presents the basic descriptive statistics of the study variables while Table 2 presents the correlation matrix between the study variable. All variables included are skewed to the right (i.e., not normally distributed) expect EUP and TOP according to Jarque-Bera (J-B) statistics and the corresponding p. values. Only GDP has a Kurtosis statistics greater than 3.

Table 1. *Descriptive statistics*

	CO_2	GDPP	$(GDPP)^2$	OIL	EUP	TOP	FDI
Mean	0.24	766.596	848957.0	43.628	410.706	27.10	520.000
Median	0.22	581.000	337561.0	27.666	400.755	29.31	1237.873
Maximum	0.38	2089.00	4363921.	94.488	491.376	47.58	2310.000
Minimum	0.11	186.000	34596.00	19.100	350.840	11.09	18.03649
Std. Dev.	0.08	516.690	1126873.	27.600	38.3193	9.61	749.000
Skewness	0.37	1.1761	1.680768	0.891	0.67965	0.10	1.021
Kurtosis	1.62	3.152	4.54	2.04	2.58	2.26	2.38
Jarque-Bera	4.78	10.88	26.78	8.01	3.97	1.15	8.92
Probability	0.0900	0.0040	0.00000	0.0183	0.1375	0.5600	0.0116
Observations	47	47	47	47	47	47	47

Table 2. *Correlation matrix*

	CO_2	GDPP	$(GDPP)^2$	OIL	EUP	TOP	FDI
CO2P	1						
GDPP	0.47	1					
$(GDPP)^2$	0.57	0.98	1				
OIL	0.54	0.85	0.84	1			
EUP	0.13	-0.65	-0.57	-0.72	1		
TOP	0.49	0.11	0.10	0.37	0.07	1	
FDI	0.56	0.80	0.78	0.97	-0.65	0.46	1

All explanatory variables are positively correlated with per capita CO_2 emissions with the highest coefficient associated with the squared GDPP followed by FDI and OIL. A correlation coefficient of value higher than 0.80 exists between GDPP, square of GDPP, OIL and FDI. EUP and TOP are not significantly correlated with other independent variables included in the study.

4.3. Econometric analysis

4.3.1. OLS estimation

Ignoring whether the time series have a unit root or not, stationary or not, we start by estimating an ordinary least squares (OLS) model as an initial step to explore the complexity of energy and economic factors affecting CO_2 emissions in Sudan as a lower middle income country. A general model form for CO_2 emissions is written as:

$$CO_2 = f(GDPP, OIL, EUP, TOP, FDI) \quad (1)$$

The econometric model to explore the effect of these factors on CO_2 emissions can be written as follows:

$$CO_2 = \alpha + \beta_1 GDPP + \beta_2 (GDPP)^2 + + \beta_3 OIL$$
$$+ \beta_4 EUP + \beta_5 TOP + \beta_6 FDI + \mu \quad (2)$$

The coefficient α is the constant (intercept) in the relationship between per capita carbon dioxide emissions and its explanatory variables.

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ and β_6 are the coefficients of CO_2 emissions with respect to GDPP, $(GDPP)^2$, OIL, EUP, TOP and FDI respectively, and μ is the standard error term. On the basis of the findings from the OLS specification, estimations and diagnosis the study proceeds to specify and estimate ARDL, an ECM and Granger causality after testing for stationarity and cointegration of the concerned variables. The data were converted into natural logarithms (L) in order to bring them to a common base, reduce their variability and enable direct estimation of elasticities. The results of OLS model are presented in table (3) and represented by equation (3).

Table 3. *Summary of OLS estimation*

	Dependent Variable	$L(CO_2)$	Std. Error	t-Statistic	Prob.
Explanatory Variable	C	-17.12	4.2922	-3.9884	0.0003***
	L(GDPP)	-2.92	0.6286	-4.6386	0.0000***
	L(GDPP)^2	0.24	0.0487	4.8597	0.0000***
	L(EUP)	3.69	0.4482	8.2378	0.0000***
	L(OIL)	0.61	0.0909	6.6720	0.0000***
	L(TOP)	0.12	0.0614	1.9623	0.0567*
	L(FDI)	-0.015	0.0068	-2.1961	0.0339**

Notes: R^2 = 0.89: Adjusted R^2 = 0.87: F-Stat = (54.44); P (0.00000): DW = 1.71; SER = 0.1209; SSR = 0.5852; LL = 36.738; AIC = -1.250; SC = -0.9746; HQC = -1.146

Diagnostic tests:

	test stat.	Prob. value	DW
Normality	0.23	0.8907	
Autocorrelation	2.38	0.6612	1.95
Heteroskidasicity	0.85	0.5372	2.49
Stability	0.09	0.7668	1.73

***, **, * indicates significance at 1%, 5% and 10% respectively.

$$co_2 = -17.12 - 2.92 gdpp + 0.24 (gdpp)^2 + 3.69 eup$$
$$+ 0.61 eup + 0.12 top - 0.015 fdi \quad (3)$$

Lower cases means that estimation is carried out on natural logarithms of the study variables. From table (3) CO_2 emissions are negatively and significantly associated with GDPP. However, the EKC does not hold for CO_2 emissions in Sudan as indicated by the positively signed and statistically significant elasticity of CO_2 emissions with respect to the square of GDPP. According the specified and estimated OLS model, CO_2 emissions in Sudan are mostly and significantly affected by energy use per capita and oil consumption, economic growth, trade openness and foreign direct investment, as indicated by their coefficients and probabilities. The coefficient of multiple determination (adjusted R^2) is reasonably high at 87%, together with F. statistic of 54.4431.766 and probability of (0.0000) indicating that the included exogenous energy and economic growth variables sufficiently explain the behaviour of CO_2 emissions in Sudan. From the diagnostic test statistics, the estimated OLS is stable and the residuals are normally distributed indicted by a J-B statistic of 0.23 and a probability of 0.8907, and suffers neither serial correlation nor heteroskidasticity. But given the likelihood of nonstationarity of the variables or their stationarity at first difference I(1) renders the OLS estimations spurious and misleading. For this reason the study proceeds with further sophisticated econometric analysis, including tests of stationary, cointegration, estimation of autoregressive distributed lag model (ARDL) with an ECM and Granger causality analysis.

4.3.2. Stationarity and cointegration of variables

The conventional Augmented Dickey-Fuller (ADF) unit root test is carried out to determine whether the variables included in the study are stationary or not and the order of integration. All variables are found to be nonstationary at level, I(0). However, all variables turn out to be stationary at first difference I(1) as presented in table (4).

Table 4. *ADF Unit Root Test and Order of Integration I(0) and I(1)*

Variable	ADF Test Statistic Value I(0)	5% Critical Value I(0)	Prob. I(0)	ADF Test Statistic Value I(1)	5% Critical Value I(1)	Prob. I(1)
L(CO_2)	-1.043	-2.928	0.730	-8.394	-2.928	0.0000*
L(GDPP)	-1.024	-2.927	0.737	-5.664	-2.928	0.0000*
L(GDPP)^2	-0.721	-2.927	0.831	-5.589	-2.928	0.0000*
L(OIL)	0.002	-2.927	0.954	-5.734	-2.928	0.0000*
L(EUP)	-2.255	-2.929	0.191	-7.270	-2.929	0.0000*
L(TOP)	-1.788	-2.927	0.382	-8.259	-2.928	0.0000*
L(FDI)	-1.131	-2.929	0.695	-8.047	-2.929	0.0000*

Notes: * indicates significance at 5 level

4.3.3. Cointegration tests

Johansen cointegration method is applied to the time series of the study in order to determine whether a long-run equilibrium relationship exists or not and then the number of cointegrating equations, if they do exist. Conitegration results presented in table (5) show that there are three cointegrating equations at 5% level of significance with a lag length of 1 on both the trace statistic and the maximum Eigen value criteria.

Table 5. *Johansen cointegration test; trace statistic and max-eigen statistic*

Null Hypotheses	Eigen Value	Trace Statistic	0.05 Critical Value	Prob.**	Max-Eigen Statistic	0.05 Critical Value	Prob.**
$r = 0$	0.666	174.607	125.615	0.0000*	49.401	46.231	0.0222*
$r \leq 1$	0.629	125.206	95.754	0.0001*	44.568	40.078	0.0146*
$r \leq 2$	0.546	80.638	69.819	0.0053*	35.529	33.877	0.0315*
$r \leq 3$	0.350	45.109	47.856	0.0886	19.416	27.584	0.3830
$r \leq 4$	0.261	25.693	29.797	0.1381	13.596	21.131	0.3990
$r \leq 5$	0.198	12.097	15.495	0.1524	9.952	14.265	0.2151
$r \leq 6$	0.047	2.145	3.841	0.1431	2.145	3.841	0.1431

Notes: Trace test indicates 3 cointegrating equations at the 0.05 level using the trace statistic and 3 cointegrating equations using the Max-Eigen statistic; * denotes rejection of the hypothesis at the 0.05 level; **MacKinnon-Haug-Michelis (1999) p-values

The cointegration test results clearly establish that a long run equilibrium relationship exists between CO_2 emissions, energy use factors and economic growth.

4.3.4. ARDL estimation

Given that the time series of variables included in the study are cointegrated of the order I(1) and there are 3 cointegrating equations using both the trace statistic and the maximum Eigen value, we proceed to estimate and autoregressive distributed lag model applying the methodology of Pesaran, Shin, & Smith, (2001). An unrestricted error correction representation of ARDL form of equation (2) can be specified as follows:

$$dco_{2_t} = \alpha + \sum_{i=1}^{p} \beta_{1i} dco_{2_{t-1}} + \sum_{i=0}^{p} \beta_{2i} dgdpp_{t-1}$$
$$+ \sum_{i=0}^{p} \beta_{3i} d(gdpp)^2{}_{t-1} + \sum_{i=0}^{p} \beta_{4i} deup_{t-i}$$
$$+ \sum_{i=0}^{p} \beta_{5i} doil_{t-i} + \sum_{i=0}^{p} \beta_{6i} dtop_{t-i} + \sum_{i=0}^{p} \beta_{7i} dfdi_{t-i}$$
$$+ \beta_8 co_{2_{t-1}} + \beta_9 gdpp_{t-1} + \beta_{10} (gdpp)_{t-1}{}^2 + \beta_{11} oil_{t-1}$$
$$+ \beta_{12} eup_{t-1} + \beta_{13} top_{t-1} + \beta_{14} fdi_{t-1} + \mu_t \quad (4)$$

Where d is the difference operator. The results of the ARDL are summarized in table (6). Note that there are 64 models evaluated and the estimated ARDL (1,1,1,0,0,0,0) is selected according to AIC criterion.

Table 6. *Summary of ARDL estimations*

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
$L(CO_2)_{t-1}$	0.34	0.109	3.134	0.0034***
L(GDPP)	1.15	1.461	0.786	0.4370
$L(GDPP)_{t-1}$	-3.08	1.483	-2.079	0.0448**
$L(GDPP)^2$	-0.09	0.114	-0.792	0.4336
$L(GDPP)^2_{t-1}$	0.25	0.116	2.130	0.0401**
L(EUP)	2.61	0.450	5.796	0.0000***
L(OIL)	0.45	0.085	5.264	0.0000***
L(TOP)	0.07	0.065	1.008	0.3198
L(FDI)	-0.01	0.007	-0.715	0.4789
C	-12.51	3.892	-3.214	0.0028***

Notes: R-squared = 0.93; Adj. R-squared = 0.91; SSR = 0.36519; SER = 0.10072; LL = 45.9563; F. Stat. = 53.758 (p. 0.0000); AIC = -1.5633; SC = -1.16579; HQC = -1.4144; DW = 2.22
*Note: p-values and any subsequent tests do not account for model selection.
Diagnostic tests:

	Test Stat.	Prob.	DW
Normality	1.37	0.5036	
Autocorrelation	0.74	0.4838	2.02
Heteroskidasticity	1.29	0.2751	2.52
Stability	0.27	0.6096	2.19

** *, ** indicate significance at 1% and 5% significance level respectively

The ARDL equation is represented as follows:

$$dco_2 p = 1.15 dgdpp - 0.09 d(gdpp)^2 + 2.61 deup + 0.45 doil$$
$$+ 0.07 dtop - 0.01 dfdi - 0.66 co_2 - 2.94 gdpp_{t-1} + 0.24 (gdpp)^2{}_{t-1}$$
$$+ 3.96 eup_{t-1} + 0.68 oil_{t-1} + 0.10 top_{t-1} - 0.01 fdi_{t-1} - 18.99 \quad (5)$$

The ARDL cointegrating short term dynamic form and long run equilibrium coefficients are presented in table (7).

Table 7. *ARDL cointegrating form and long run coefficients*

Cointegrating Short Run Dynamics					Long Run Equilibrium				
Variable	Coeff.	Std. Error	t-Stat.	Prob.	Variable	Coeff.	Std. Error	t-Stat.	Prob.
dL(GDPP)	1.15	1.461	0.786	0.4370	$L(GDPP)_{t-1}$	-2.94	0.920	-3.1927	0.0029*
$d(L(GDPP)^2$	-0.09	0.114	-0.792	0.4336	$L(GDPP)^2_{t-1}$	0.24	0.071	3.3535	0.0019*
dL(EUP)	2.61	0.450	5.796	0.0000*	$L(EUP)_{t-1}$	3.96	0.719	5.5133	0.0000*
dL(OIL)	0.45	0.085	5.264	0.0000*	$L(OIL)_{t-1}$	0.68	0.132	5.1187	0.0000*
dL(TOP)	0.07	0.065	1.009	0.3198	$L(TOP)_{t-1}$	0.10	0.091	1.0973	0.2798
dL(FDI)	-0.01	0.007	-0.715	0.4789	$L(FDI)_{t-1}$	-0.008	0.010	-0.7586	0.4530
ECT_{t-1}	-0.66	0.109	-6.0499	0.0000*	C	-18.99	6.710	-2.8305	0.0076*

Notes: * indicates significance at 1% level of Significance

The ARDL results show that economic growth, energy use per capita and oil have significant effect on CO_2 emissions in the long term, but not trade openness and foreign direct investment. At low level of GDPP, economic growth leads to decreasing trend of CO_2 emissions but squaring GDPP over time leads to increasing amounts of CO_2 emissions a finding contradict the claim of the EKC hypothesis. In the short run, CO_2 emissions are found to be only significantly affected by oil consumption and total energy use per capita. The ARDL results show that the dependent variable CO_2 emissions converges to equilibrium position at a factor of 0.66 each year. The reliability of the estimated ARDL is tested through the known diagnosis tests and the results are summarized in table (6).

4.3.4. Granger causality test

Since the ARDL does not show the direction of causality amongst the variables of the study, the study performs a Granger causality test. Out of 42 possible causalities between CO_2 emissions and its specified explanatory variables at lag length of 2, it turns out there are 18 significant causal relationships, representing 43%. This indicates that the specified and estimated model can be deemed as sufficient and indicates the power of the model. Summary results of Granger causality relationships are presented in table (8). A unidirectional relationship exists between CO_2P emissions and GDPP, running from GDPP and its squared value to CO_2, meaning that GDPP causes CO_2P emissions and not vice versa confirming Halicioglu, (2009) for the case of Turkey. Our results also match those of Zhang & Cheng (2009) for the case of China as they find that income and energy use are Granger causing carbon emissions. Our model also shows existence of Granger causality relationship running from OIL to CO_2 emissions and not vice versa but only significant at 10%. Both the results on economic growth and energy use in our study confirm the findings of Omri (2009) for a panel of 14 MENA countries. The FDI is found to be Granger causing CO_2 emissions with no sign of feedback effect. As for the relationship between energy and economic growth, only oil consumption is found to Granger causing economic growth in terms of both GDPP and the squared value of GDPP.

Table 8. *Summary of pair wise Granger causality test*

Null Hypothesis H_0:	Obs.	F-Statistic	Prob.	Conclusion
H_0: *L(GDPP)* does not Granger cause *L(CO₂)*	45	3.154	0.0535	Reject H_0
H_0: *L(CO₂)* does not Granger cause *L(GDPP)*	45	1.377	0.2640	Accept H_0
H_0: $L(GDPP)^2$ does not Granger cause $L(CO_2)$	45	3.247	0.0494	Reject H_0
H_0: $L(CO_2)$ does not Granger cause $L(GDPP)^2$	45	1.356	0.2692	Accept H_0
H_0: *L(OIL)* does not Granger cause $L(CO_2)$	45	3.021	0.0600	Reject H_0
H_0: $L(CO_2)$ does not Granger cause *L(OIL)*	45	1.505	0.2344	Accept H_0
H_0: *L(EUP)* does not Granger cause $L(CO_2)$	45	1.549	0.2249	Accept H_0
H_0: $L(CO_2)$ does not Granger cause *L(EUP)*	45	2.069	0.1397	Accept H_0
H_0: *L(TOP)* does not Granger cause $L(CO_2)$	45	0.583	0.5629	Accept H_0
H_0: $L(CO_2)$ does not Granger cause *L(TOP)*	45	2.187	0.1255	Accept H_0
H_0: *L(FDI)* does not Granger cause $L(CO_2)$	45	5.803	0.0061	Reject H_0
H_0: $L(CO_2)$ does not Granger cause *L(FDI)*	45	0.284	0.7539	Accept H_0
H_0: *L(EUP) does not Granger cause L(GDPP)*	45	0.4575	0.6361	Accept H_0
H_0: *L(GDPP) does not Granger cause L(EUP)*	45	0.8512	0.4345	Accept H_0
H_0: *L(OIL) does not Granger cause L(GDPP)*	45	4.9512	0.0120	Reject H_0
H_0: *L(GDPP) does not Granger cause L(OIL)*	45	0.2291	0.7963	Accept H_0
H_0: *L(EUP) does not Granger cause* $L(GDPP)^2$	45	0.4862	0.6185	Accept H_0

H_0: L(GDPP)^2 does not Granger cause L(EUP)	45	0.5997	0.5539	Accept H_0
H_0: L(OIL) does not Granger cause L(GDPP)^2	45	4.9407	0.0121	Reject H_0
H_0: L(GDPP)^2 does not Granger cause L(OIL)	45	0.2612	0.7714	Accept H_0

5. Conclusion and Recommendations

This study is an empirical one in investigating energy and economic growth related factors in explaining the behaviour of CO_2 emissions in Sudan over the period 1969-2015. The OLS estimated model shows the significant effects of GDP per capita, oil consumption per capita, energy use per capita, trade openness, foreign direct investment on CO_2 emissions per capita in Sudan. The OLS results show significant relationship between the squared GDPP and CO_2 emissions but positively signed coefficient contradicting the EKC claim. The ARDL results confirm non-existence of and EKC as well as showing that oil consumption, energy use and GDP growth as the main deriving factors behind CO_2 emissions in Sudan in the long term. Neither trade openness nor foreign direct investment has effect on CO_2 emissions in the long run. Granger causality test shows existence of bidirectional relationship running from GDPP value and the squared GDPP to CO_2 emissions. In this sense economic growth in Sudan is associated with environmental degradation and it is expected as Sudan is still an underdeveloped country. In part, our findings are consistent with Soytas, Sari & Ewing (2007) who find that energy use is Granger causing carbon emissions in US. But our findings contradict them in that income does not Granger cause carbon emissions in the US in the long run while income is found to be Granger causing CO_2 emissions in Sudan. Oil and FDI are found to be Granger causing CO_2 emissions and not the vice versa. The study recommends that energy efficiency measures in terms of proper pricing of oil derivatives, expansion of production and use of liquefied petroleum gas (LPG) and restrictions in production and use of fuel woods and charcoal with sustainability pricing should be adopted. These measures are needed because it is unlikely for a low income country like Sudan to reduce energy use per capita which is already low and energy use per unit of output needed for foresting economic growth. Impacts of FDI need to be assessed and environmentally regulated.

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