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January 2017

A G D I Working Paper

WP/17/039

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Forthcoming: Technological Forecasting and Social Change

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Abstract

This study examines how increasing ICT penetration in sub-Saharan Africa (SSA) can contribute towards environmental sustainability by decreasing CO_2 emissions. The empirical evidence is based the Generalised Method of Moments and forty-four countries for the period 2000-2012. ICT is measured with internet penetration and mobile phone penetration while CO_2 emissions per capita and CO_2 emissions from liquid fuel consumption are used as proxies for environmental degradation. The following findings are established: First, from the non-interactive regressions, ICT (i.e. mobile phones and the internet) does not significantly affect CO_2 emissions. Second, with interactive regressions, increasing ICT has a positive net effect on CO_2 emissions per capita while increasing mobile phone penetration alone has a net negative effect on CO_2 emissions from liquid fuel consumption. Policy thresholds at which ICT can change the net effects from positive to negative are computed and discussed. These policy thresholds are the minimum levels of ICT required, for the effect of ICT on CO_2 emissions to be negative. Other practical implications for policy and theory are discussed.

JEL Classification: C52; O38; O40; O55; P37
Keywords: CO_2 emissions; ICT; economic development; Sub-Saharan Africa

1. Introduction

It is difficult to achieve sustainable development and environmental protection without three main elements, namely: accountability, transparency and the wider participation of the public through information flow (Chemutai, 2009). The third element requires the availability of a communication tool that enables diffusion of knowledge, in order to reduce the informational/knowledge deficiencies that are associated with environmental degradation. CO_2 emissions contribute to environmental degradation or pollution. Hence in this study, the amount of pollution caused by CO_2 emissions will be used as a proxy for environmental degradation. This study is concerned with assessing how enhancing information and communication technology (ICT) can affect the emission of a greenhouse gas such as CO_2.[1]

The positioning of the inquiry is motivated by four main trends in policy and scholarly circles, namely: the need for effective communication strategies in environmental governance for multilateral policy coordination; the great potential for the penetration of ICT in Sub-Saharan Africa (SSA); issues pertaining to global warming and environmental sustainability; and gaps in the existing literature. These trends are considered in further detail below.

First, communication as a tool for environmental management has often been overlooked as part and parcel of environmental governance. With regard to the United Nations Task Force on Environment and Human Settlements credible governance of the environment can exclusively be achieved via effective coordination at national levels. The narrative further notes that only through effective communication can departments which provide consistent guidance to special agencies on environmental management respond to specific requirements within the government. While a comprehensive implementation of Multilateral Environmental Agreements (MEAs) and Agenda 21[2] is achievable via advanced communications among secretariats of MEA, it is important to share environmental databases among institutions, in order to address challenges like false reporting and other information asymmetries (Chemutai, 2009).

Second, recent ICT literature is consistent with the view that compared to other more advanced economies in the world (Asia, Europe & North America) where ICT is reaching levels of saturation, there is more room for ICT penetration in SSA (see Penard et al., 2012; Asongu, 2013; Afutu-Kotey et al., 2017; Asongu & Nwachukwu, 2016a). Such a promising

[1] For the purpose of simplicity, in some narratives, the terms ICT, the internet and mobile phones are used interchangeably.

[2] Agenda 21 is one of the United Nation's voluntarily implemented plans of action that is non-binding with respect to sustainable development.

potential for penetration can be leveraged by policy makers in order to address sobering policy challenges to sustainable development, such as environmental pollution and global warming.

Third, environmental sustainability by means of mitigating greenhouse gas (such as CO_2) emissions is a pressing agenda for the achievement of the Sustainable Development Goals (SDGs) (see Asongu et al., 2016a). This is particularly relevant for SSA because of the recent growth resurgence of the sub-region; the persistent energy crisis in the sub-region; poor energy management and consequences of climate change.

Over the last two decades, Africa has been experiencing a recent phase of growth resurgence after several decades of lost growth, due partly to failed Structural Adjustment Programmes (SAP) (see Fosu, 2015). Some accounts maintain that SSA has recently hosted about seven of the World's ten fastest growing economies (Asongu & Rangan, 2016).

However, the management of energy in the sub-region has not been effective, in spite of the apparent energy crisis which represents one of the most critical policy syndromes in the post-2015 development era.[3] Shurig (2015) found that access to electrical energy in the sub-region is limited to 5% of the population. Moreover, the consumption of energy in SSA is below 17% of the global average: the equivalent of energy consumed by a single state such as New York, USA.

Inefficiency has recently characterised the management of energy in most African nations (Anyangwe, 2014). To put this point into perspective, Nigeria - the most populous country in Africa, devotes a large proportion of government resources to subsidising the use of fossil fuels, instead of investing in alternative and renewable energy sources. This has led to the use of electricity generators (that burn subsidised petroleum fuel) to compensate for outages of and shortages in electricity supply (see Apkan & Apkan, 2012).

It is now abundantly clear that global warming which is one of the most dominant challenges in the post-2015 development era, is a direct consequence of the unsustainable consumption of fossil fuels (see Huxster et al., 2015). Unfortunately, compared to other regions of the world, Africa may be most severely affected by the negative effects associated with global warming (Kifle, 2008), partly because compared to other continents of the world

[3]Fosu (2013) defines policy syndromes as situations that are detrimental to growth: 'administered redistribution', 'state breakdown', 'state controls', and 'suboptimal inter temporal resource allocation'. Within the framework of this study, policy syndromes are considered as issues that merit policy action in order to achieve sustainable development.

Africa lacks adequate financial resources with which to deal with the consequences of global warming. This sobering prospect is broadly shared by Akpan and Akpan (2012) who have posited that CO_2 emissions constitute about three-quarter of the world's emissions in greenhouse gas, which cause global warming.

Fourth, this inquiry unites the three strands above by examining how enhancing ICT affects environmental sustainability through the reduction of CO_2 emissions. In addition to insights supporting the inquiry discussed in the previous paragraphs, the intuition motivating the inquiry is that by sharing information and potentially decreasing corresponding information asymmetry, ICT can reduce transaction and travelling costs that are associated with the CO_2 emissions in households and corporations. Such intuition can be framed in theory-building, as opposed to the testing of theory. Accordingly, given that practical and policy implications will be provided by the study, we are consistent with the literature (see Costantini & Lupi, 2005; Narayan et al., 2011) in arguing that applied econometrics should not exclusively be based on the rejection and acceptance of existing theories. This is essentially because an empirical exercise that is founded on solid intuition could pave the way towards theory-building, especially in the light of growing SDGs challenges.

The positioning of this study deviates from existing literature which has been fundamentally based on investigating nexuses between energy consumption, CO_2 emissions and economic growth. While the first strand of this extant literature focuses on the relationship between environmental pollution and economic growth with particular articulation on the Environmental Kuznets Curve (EKC) hypothesis (see Diao et al., 2009; Akbostanci et al., 2009; He & Richard, 2010),[4] the second strand is concerned with linkages between energy consumption, economic growth and environmental pollution (Jumbe, 2004; Ang, 2007; Odhiambo, 2009a, 2009b; Apergis & Payne, 2009; Menyah & Wolde-Rufael, 2010; Ozturk & Acaravci, 2010; Begum et al., 2015; Bölük & Mehmet, 2015) and nexuses between the consumption of energy and economic growth (Mehrara, 2007; Esso, 2010).

A common drawback to the highlighted studies is the absence of a policy variable with which associated policy syndromes underlying the inquiries can be addressed. We argue that inquiries motivated by nexuses between policy syndromes (CO_2 emissions) and macro economic variables (e.g. energy consumption and economic growth) provide results with limited policy relevance because policy makers are not provided with policy instruments with

[4] According to the EKC hypothesis, in the long term, there is an inverted U-shaped relationship between per capita income and environmental degradation.

which to address associated policy syndromes. The highlighted gap is addressed using ICT as a policy variable. In essence, we investigate how increasing ICT penetration can reduce CO_2 emissions by establishing relevant mobile phone penetration and internet penetration thresholds above which ICT penetration reduces CO_2 emissions.[5]

The current paper deviates from the recent ICT literature which has fundamentally focused on, *inter alia*: Africa's information revolution from the perspective of production networks and technical regimes (Murphy & Carmody, 2015); economic prosperity (Levendis & Lee, 2013; Qureshi, 2013a); banking sector progress (Kamel, 2005); living standards (Chavula, 2013); externalities in welfare (Carmody, 2013; Qureshi, 2013bc); life for all (Kivuneki et al., 2011) and sustainable development (Byrne et al., 2011) in developing nations. Hence, whereas human development and socioeconomic benefits associated with ICT have been substantially documented in the existing literature, we contribute to this stream of engaged literature by assessing how ICT can be consolidated for environmental sustainability. Accordingly, we have built on a comprehensive survey of green ICT literature (see Krishnadas & Radhakrishna, 2014) and more contemporary studies to position the study.

The above positioning is also an extension of recent technological foresight literature on the role of technology and innovation in sustaining development and corporate outcomes, notably: the exploration of battery technology for grid-related energy storage (Versteeg et al., 2017); techno-organisational decarbonisation (Mazzanti & Rizzo, 2017); the importance of technology in consolidating the petroleum and petrochemical industry (Hossani et al., 2017); the relevance of environmental innovation in marketing capacity (Yu et al., 2017); linkages between unburnable fossil fuel, cumulative emissions and optimal carbon tax (van de Ploeg & Rezai, 2017) and the connection of innovation ecosystems (Pombo-Juárez et al., 2017).

The inquiry we are engaging is relevant for policy because communication, which is essential in the coordination of good environmental governance, has often been neglected in policy circles (see Chemutai, 2009). According to the narrative, the United Nations Task Force on Environment and Human Settlements and environmental protection can be achieved fundamentally through effective coordination with good communication tools.

[5] Accordingly, thresholds articulate levels of ICT penetration that are essential in reducing CO_2 emissions. This objective does not suggest the existence of ICT thresholds that may be trivial if changes in some factors (e.g. desertification due to land clearing and overgrazing) contribute to decreasing CO_2 emissions. Hence, the attainment of this objective does not negate the relevance of other factors in decreasing CO2 emissions.

The rest of the study is structured as follows. Section 2 engages the data and methodology. The empirical results are presented in Section 3 and Section 4 concludes with implications and future research directions.

2. Data and methodology

This study investigates a panel of forty-four countries in SSA with data from African Development Indicators of the World Bank for the period 2000-2012.[6] While we have provided the motivation for the scope of the inquiry in the introduction, the corresponding periodicity is contingent on constraints in data availability. The dependent variables are: CO_2 emissions per capita and CO_2 emissions from liquid fuel consumption. In the corresponding assessment, a negative effect on the outcome variables indicates environmental protection or sustainability.

Consistent with recent ICT literature, the internet and the mobile phone are used as proxies that measure ICT (Penard et al., 2012; Asongu, 2014; Tony & Kwan, 2015; Amavilah et al., 2017; Tchamyou, 2016). Therefore, the internet penetration rate (per 100 people) and the mobile phone penetration rate (per 100 people) are used as ICT policy variables. In order to reduce concerns about variable omission bias, five control variables are used, namely: trade openness, Gross Domestic Product (GDP) growth, population growth, quality of education and regulation quality. Hence, the variables account for: globalisation (trade openness), the market (GDP growth and population growth), institutional quality (regulation quality) and other human factors (quality of education).

Intuitively, we expect the quality of education and regulation quality to negatively affect the outcome variables, while trade openness and population are expected to have the opposite effect. The effect of GDP growth is ambiguous because it is contingent on a plethora of factors, notably, whether, GDP growth is broad-based or limited to a select number of industries and whether the fruits from economic prosperity are used to finance conditions for sustainable development. Conversely it may be seen that growing GDP may also contribute to environmental damages. It is also worthwhile to balance the expectations in signs with the fact that country-specific features that are eliminated (by definition) from the Generalised

[6] The 44 countries are: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo Democratic. Republic., Congo Republic, Cote d'Ivoire, Djibouti, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda and Zambia.

Method of Moments (GMM) specifications may weight on the expected signs. Moreover, population growth and GDP growth dynamics could be high in Africa, which could generate some biases in the expected signs. This study assumes that primary education is a basic condition for ICT literacy. In our study, we assume that primary education is a necessary condition for ICT literacy. The full definitions of variables, corresponding summary statistics and correlation matrix can be found in Appendix 1, 2 and 3 respectively. While the correlation matrix is reported, issues of multicollinearity are not relevant in interactive regressions (see Brambor et al., 2006). The Shapiro-Wilk normality test is also provided in Appendix 2 to show that the variables are not normally distributed. Hence, estimation techniques like Ordinary Least Squares are inappropriate.

In the estimation process, we adopt a *two-step* GMM empirical strategy for five principal reasons: (i) the number of countries (44) is higher than the number of years in each country (13); (ii) the outcome variables are persistent because their correlation coefficients with their respective first lags are higher than the rule thumb threshold of 0.800; (iii) given that the GMM approach (by definition) builds on a panel data structure, cross-country differences are considered in the regressions; (iv) the estimation approach further controls for endogeneity by accounting for simultaneity in the exploratory variables through the process of instrumentation and use of time-invariant omitted variables and (v) inherent biases in the *difference* estimator are corrected with the *system* estimator.

In this study, the Arellano and Bover (1995) extension by Roodman (2009ab) is employed because, relative to traditional GMM techniques (*difference* and *system* GMM approaches), it mitigates the proliferation of instruments (or restricts over-identification) and accounts for cross-sectional dependence (Love & Zicchino, 2006; Baltagi, 2008; Boateng et al., 2016).

The following equations in level (1) and first difference (2) summarise the standard *system* GMM estimation procedure in which the error term take a two-way error component form.

$$CO_{i,t} = \sigma_0 + \sigma_1 CO_{i,t-\tau} + \sigma_2 IC_{i,t} + \sigma_3 ICIC_{i,t} + \sum_{h=1}^{5} \delta_h W_{h,i,t-\tau} + \upsilon_{i,t} \quad (1)$$

$$CO_{i,t} - CO_{i,t-\tau} = \sigma_1 (CO_{i,t-\tau} - CO_{i,t-2\tau}) + \sigma_2 (IC_{i,t} - IC_{i,t-\tau}) + \sigma_3 (ICIC_{i,t} - ICIC_{i,t-\tau}) + \sum_{h=1}^{5} \delta_h (W_{h,i,t-\tau} - W_{h,i,t-2\tau}) + (\upsilon_{i,t} - \upsilon_{i,t-\tau}) \quad (2)$$

$$\upsilon_{i,t} = \eta_i + \xi_t + \varepsilon_{i,t} \quad (3)$$

$$\upsilon_{i,t} + \upsilon_{i,t-\tau} = (\xi_t - \xi_{t-\tau}) + (\varepsilon_{i,t} + \varepsilon_{i,t-\tau}) \quad (4)$$

where, $CO_{i,t}$ is a CO_2 emissions indicator of country i at period t; σ_0 is a constant, IC represents information and communication technology (mobile phone penetration and internet penetration); $ICIC$ is the interaction between identical ICT variables (e.g. "mobile phones × mobile phones" or "internet ×internet"); W is the vector of control variables (*trade*, *GDP growth*, *population growth*, *education* and *regulation quality*); τ represents the coefficient of auto-regression, which is one for the specification, because of limited degrees of freedom; ξ_t is the time-specific constant; η_i is the country-specific effects (or factors that are particular to each country in the sample), $\upsilon_{i,t}$ is the two-way the disturbance term and $\varepsilon_{i,t}$ is the error term. The definitions and sources of the variables can be found in Appendix 1.

We now devote space to discussing the identification and exclusion restriction strategy which is important for a sound GMM specification. In accordance with recent studies, we consider all the explanatory variables as predetermined or suspected endogenous and exclusively acknowledge the time invariant variables to exhibit strict exogeneity (Boateng et al., 2016; Asongu & Nwachukwu, 2016b). Within this framework, Roodman (2009b) has argued that it is not very feasible for time-invariant variables to be endogenous after a first difference.[7]

As concerns exclusion restrictions, consistent with the process of identification discussed above, the time invariant variables affect the outcome CO_2 emissions indicators exclusively through the suspected endogenous channels. Furthermore, the criterion employed to assess the statistical relevance of this identification strategy is the Difference in Hansen Test (DHT) for instrument exogeneity. Hence, in order for the hypothesis of exclusion restriction to hold, the null hypothesis of the DHT should not be rejected. Failure to reject this hypothesis is an indication that CO_2 emissions are influenced exclusively by the strictly exogenous variables, through the suspected endogenous indicators.

[7] Hence, the procedure for treating *ivstyle* (years) is 'iv (years, eq(diff))' whereas the *gmmstyle* is employed for predetermined variables (Asongu & De Moor, 2017).

In the light of the above emphasis, the assumption of exclusion restriction is confirmed in the reported results, when the null hypothesis of the DHT related to instrumental variables (IV) (year, eq(diff)) is not rejected. This process in GMM exclusion restriction is broadly consistent with the standard instrumental variable (IV) procedure, in which failure to reject the null hypothesis of the Sargan Overidentifying Restrictions (OIR) test is implies that strictly exogenous variables affect the outcome variable exclusively via the suspected endogenous variable channels (see Beck et al., 2003; Asongu & Nwachukwu, 2016c).

3. Empirical results

Table 1 below presents the empirical results. There are two main sets of specifications pertaining to the two dependent variables. For either dependent variable, there are two subsets of specifications. Each sub-specification is characterised by 'mobile phone'- and 'internet'-related regressions.

Four main information criteria are employed to assess whether the GMM models are valid.[8] It is important to articulate two more points in the light of these information criteria. On the one hand, the second-order Arellano and Bond autocorrelation test (AR(2)) is more relevant as an information criterion than the first-order because some studies exclusively report the higher order with no disclosure of the first order (e.g. see Narayan et al., 2011; Asongu & Nwachukwu, 2016d). On the other hand, the Hansen test is robust but weakened by instruments whereas the Sargan test is not robust but not weakened by instruments. "Weakened by instruments" implies that employing too many instruments increases the probability of a Type 2 error (i.e. failure to reject a false null hypothesis) or not rejecting the null hypothesis for the validity of instruments. A logical way of addressing the conflict is to adopt the Hansen test and avoid the proliferation of instruments. Instrument proliferation is subsequently avoided by ensuring that the number of instruments in each specification is lower than the corresponding number of cross sections.

Net effects are computed to examine the overall effect of increasing ICT on environmental sustainability. For instance, in the third column of Table 1, the net effect from

[8] "*First, the null hypothesis of the second-order Arellano and Bond autocorrelation test (AR (2)) in difference for the absence of autocorrelation in the residuals should not be rejected. Second, the Sargan and Hansen over-identification restrictions (OIR) tests should not be significant because their null hypotheses are the positions that instruments are valid or not correlated with the error terms. In essence, while the Sargan OIR test is not robust but not weakened by instruments, the Hansen OIR is robust but weakened by instruments. In order to restrict identification or limit the proliferation of instruments, we have ensured that instruments are lower than the number of cross-sections in most specifications. Third, the Difference in Hansen Test (DHT) for exogeneity of instruments is also employed to assess the validity of results from the Hansen OIR test. Fourth, a Fischer test for the joint validity of estimated coefficients is also provided*" (Asongu & De Moor, 2017, p.200).

enhancing mobile phone penetration is 0.0025 ([-0.00002 × 24.428] + [0.003]). In the computation, the mean value of mobile phone penetration is 24.428, the unconditional effect of mobile phone penetration is 0.003, while the marginal effect from increasing mobile phones is -0.00002. This labelling of effects is consistent with recent literature on increasing ICT for development outcomes (Asongu & Le Roux, 2017).

The following findings can be established from Table 1. First, from the non-interactive regressions, ICT (i.e. mobile phones and the internet) does not significantly affect CO_2 emissions. Second, with regard to the interactive regressions, increasing ICT has a positive net effect on per capita CO_2 emissions, while increasing mobile phones *alone* would have a negative net negative effect on CO_2 emissions from liquid fuel consumption. Third, the "hysteresis" hypothesis is apparent because the absolute values of estimated lagged dependent variables are consistently between the intervals of zero and one, implying that past values of CO_2 emissions have a positive influence on future CO_2 emissions. The information criterion for the "hysteresis" hypothesis is consistent with recent literature (Fung, 2009, p. 58; Prochniak & Witkowski, 2012a, p. 20; Prochniak & Witkowski, 2012b, p. 23). Most of the significant control variables have signs as expected and detailed before.

Table 1: Enhancing ICT and CO_2 emissions

	Dependent variables: CO_2 emissions							
	CO_2 emissions (metric tons per capita)				CO_2 emissions from liquid fuel consumption (% of total)			
	Mobile		Internet		Mobile		Internet	
Constant	**0.446*** **	**0.227*** **	**0.621*** **	**0.340*** **	-4.088	1.038	**-6.464** **	**-5.532** **
	(0.000)	**(0.003)**	**(0.000)**	**(0.000)**	(0.107)	(0.618)	**(0.036)**	**(0.044)**
CO_2 per capita (-1)	**0.897*** **	**0.934*** **	**0.924*** **	**0.929*** **	---	---	---	---
	(0.000)	**(0.000)**	**(0.000)**	**(0.000)**				
CO_2 from fuel (-1)	---	---	---	---	**0.980*** **	**0.950*** **	**0.974*** **	**0.990*** **
					(0.000)	**(0.000)**	**(0.000)**	**(0.000)**
Mobile	0.00002	**0.003*** **	---	---	0.010	**-0.047** **	---	---
	(0.962)	**(0.000)**			(0.372)	**(0.038)**		
Mobile ×Mobile	---	**-0.00002*** **	---	---	---	**0.0005*** **	---	---
		(0.000)				**(0.000)**		
Internet	---	---	-0.001	**0.017*** **	---	---	**0.056* **	-0.120
			(0.147)	**(0.000)**			**(0.050)**	(0.105)
Internet×Internet	---	---	---	**-0.0004*** **	---	---	---	**0.004*** **
				(0.000)				**(0.007)**
Trade	-0.0003	**-0.0006** **	**-0.001* **	**-0.001*** **	0.013	0.0006	**0.030** **	**0.024* **
	(0.222)	**(0.042)**	**(0.051)**	**(0.001)**	(0.166)	(0.949)	**(0.029)**	**(0.065)**
GDP growth	0.0001	**-0.002** **	-0.002	**-0.002** **	-0.020	**-0.053** **	-0.020	-0.013
	(0.930)	**(0.049)**	(0.143)	**(0.044)**	(0.454)	**(0.024)**	(0.539)	(0.641)
Population growth	**-0.072*** **	**-0.075*** **	**-0.116*** **	**-0.072*** **	**1.189** **	**1.460*** **	**0.954** **	**0.803*** **
	(0.000)	**(0.000)**	**(0.000)**	**(0.000)**	**(0.023)**	**(0.002)**	**(0.019)**	**(0.000)**
Education	**-0.004*** **	-0.0008	**-0.004*** **	-0.001	**0.041* **	-0.005	**0.087*** **	**0.069** **
	(0.000)	(0.536)	**(0.004)**	(0.228)	**(0.087)**	(0.793)	**(0.002)**	**(0.012)**
Regulation Quality	0.005	**-0.090* **	-0.050	-0.025	0.857	0.632	1.421	**1.853** **
	(0.861)	**(0.050)**	(0.254)	(0.393)	(0.426)	(0.574)	(0.132)	**(0.036)**
Time Effects (2000-2012)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Net Effects	nsa	0.0025	nsa	0.0153	nsa	-0.0347	nsa	na
AR(1)	(0.109)	(0.095)	(0.105)	(0.099)	(0.006)	(0.007)	(0.004)	(0.004)
AR(2)	**(0.207)**	**(0.199)**	**(0.149)**	**(0.153)**	(0.046)	(0.044)	(0.033)	(0.032)
Sargan OIR	(0.000)	(0.000)	(0.000)	(0.000)	**(0.826)**	**(0.952)**	**(0.954)**	**(0.980)**
Hansen OIR	**(0.861)**	**(0.390)**	**(0.783)**	**(0.361)**	**(0.372)**	**(0.610)**	**(0.682)**	**(0.829)**
DHT for instruments								
(a)Instruments in levels								
H excluding group	**(0.754)**	**(0.726)**	**(0.871)**	**(0.828)**	**(0.865)**	**(0.971)**	**(0.528)**	**(0.636)**
Dif(null, H=exogenous)	**(0.763)**	**(0.225)**	**(0.566)**	**(0.165)**	**(0.163)**	**(0.274)**	**(0.652)**	**(0.784)**
(b) IV (years, eq(diff))								
H excluding group	**(0.743)**	**(0.594)**	**(0.978)**	**(0.573)**	**(0.140)**	**(0.271)**	**(0.287)**	**(0.617)**
Dif(null, H=exogenous)	**(0.765)**	**(0.213)**	**(0.285)**	**(0.197)**	**(0.779)**	**(0.914)**	**(0.932)**	**(0.850)**
Fisher	**20560*** **	**84884*** **	**6308*** **	**287100*** **	**1143*** **	**2558*** **	**462.85*** **	**5779*** **
Instruments	36	40	36	40	36	40	36	40
Countries	44	44	43	43	44	44	43	43
Observations	339	339	334	334	339	339	334	334

*,**,***: significance levels of 10%, 5% and 1% respectively. The different significant levels reported in the table are standard levels of significance used in the literature, notably: 10%, 5% and 1% significance levels. DHT: Difference in Hansen Test for Exogeneity of Instruments' Subsets.
Dif: Difference. OIR: Over-identifying Restrictions Test.
The significance of bold values is twofold. 1) The significance of estimated coefficients and the Fisher statistics. 2) The failure to reject the null hypotheses of: a) no autocorrelation in the AR(1) and AR(2) tests and b) the validity of the instruments in the Sargan and Hansen OIR tests. Whereas eqs (1) and (2) represent the standard system GMM specification, the results reported in Table 1 are based on the system GMM in the perspective of Roodman (2009a, 2009b).
nsa: not specifically applicable because the regressions is non interactive. na: not applicable because at least one estimated coefficient needed for the computation of net effects is not significant.
The mean of mobile phone penetration is 24.428 while the mean of internet penetration is 4.222.

We have established that increasing ICT would have positive net impacts on CO_2 emissions per capita. Fortunately, the corresponding marginal effects are negative. The implication of these negative marginal effects is that at certain thresholds of ICT, the net impact can be changed from positive to negative. Accordingly, in order for these thresholds to make economic sense and have policy relevance, they must be within the range of corresponding data. Such a range denotes the minimum to maximum values provided by the summary statistics. In what follows, we first clarify the concept of threshold before computing the thresholds corresponding to the net positive effects.

The conception of threshold (also referred to as critical mass) represents a point at which, further ICT penetration yields a net negative effect on CO_2 per capita emissions. Hence, if the computed thresholds are within statistical range, policy makers can aim to increase ICT penetration beyond the established thresholds, in order to achieve the desired effect on environmental sustainability. This notion of threshold is consistent with the literature, notably: critical masses for appealing effects (Roller & Waverman, 2001; Batuo, 2015); requirements for inverted U-shaped and U-shaped patterns (see Ashraf & Galor, 2013), minimum conditions for desired impacts (Cummins, 2000) and essential information sharing thresholds at which market power can be curbed in order to enhance financial intermediation efficiency (Asongu et al., 2016b).

The following are the corresponding critical thresholds of ICT penetration in reducing CO_2 emissions: (i) 150(0.003/0.00002) for mobile phone penetration per 100 people and (ii) 42.5(0.017/0.0004) for internet penetration per 100 people. Given that the mobile penetration range is between 0.000 and 147.202 per 100 people, only the computed threshold of internet penetration makes economic sense and has policy relevance. It follows that increasing the internet penetration rate to above 42.5 per 100 people, would mitigate CO_2 per capita emissions and enhance environmental sustainability. Thus, the calculated policy threshold is the minimum level of ICT required, for the effect of ICT on CO_2 emissions to be negative.

4. Concluding implications, caveats and future research directions

This study has examined how increasing ICT penetration in Sub-Saharan Africa (SSA) can contribute towards environmental sustainability by decreasing CO_2 emissions. The empirical evidence is based on Generalised Method of Moments and forty-four countries for the period 2000-2012. ICT is measured with internet penetration and mobile phone penetration, while CO_2 emissions per capita and CO_2 emissions from liquid fuel consumption are used as proxies for CO_2 emissions. The following findings have been established. First, from the non-interactive regressions we conclude that increasing ICT (i.e. mobile phones and the internet) would not significantly affect CO_2 emissions. Second, using the interactive regressions we conclude that increasing ICT has a positive net effect on CO_2 emissions per capita, while increasing mobile phone penetration has a net negative effect on CO_2 emissions from liquid fuel consumption.

The negative net effects imply that ICT needs to be further consolidated beyond certain thresholds, in order to achieve the desired negative net effect on CO_2 emissions per capita. We have computed these corresponding thresholds and found them to be: 150 per 100 people for mobile phone penetration and 42.5 per 100 people for internet penetration. While the former is not within practical range, and thus has no practical implication for policy, the latter is within achievable range and is of policy relevance. It follows that an internet penetration range of above 42.5 for every 100 people ensures environmental sustainability by reducing CO_2 emissions per capita.

The main policy implication of the findings is that ICT can be practically consolidated in order to mitigate CO_2 emissions per capita. The fact that the threshold at which this is possible exclusively make economic sense for internet penetration is appealing, because the internet can be used on many devices, such as the mobile phone. Hence, the internet is intuitively more relevant than the mobile phone, though both are also complementary.

Policy makers can leverage on the established findings in the post-2015 development era, by addressing issues related to internet penetration, like affordability and lack of infrastructure. Furthermore, universal access that encourages low pricing and broad coverage should also be considered. In order to sustainably mitigate CO_2 per capita emissions, such internet penetration policy should be tailored to encourage the adoption, access, interactions, effectiveness and reach of ICT. This policy agenda can go a long way towards making progress on some stalling environmental objectives, namely: Agenda 21 and Multilateral Environmental Agreements (MEAs). National schemes like the Rwanda Information Technology Authority (RITA) should be encouraged in other African countries. RITA consolidates and coordinates the nation's resources in information technology (Chemutai, 2009).

The principal theoretical contribution of the study is that ICT reduces information asymmetry associated with environmental pollution. Therefore, by decreasing informational rents that are associated with CO_2 emissions, the theoretical relevance of ICT is consistent with the theoretical underpinnings of information sharing offices (e.g. private credit bureaus and public credit registries) in decreasing information asymmetry for banking intermediation efficiency (see Tchamyou & Asongu, 2017; Asongu et al., 2016c). In the light of this analogy, the theoretical motivation for consolidating financial intermediation efficiency through information sharing offices is consistent with the use of ICT to tailor efficiency in CO_2 emissions for environmental sustainability. Such efficiency is both intuitive and practical because ICT can be instrumental in sharing information to reduce unnecessary travelling and corresponding CO_2 emissions and boost household and public management efficiency through the use of energy-saving ICT applications.

The importance of ICT in dampening CO_2 emissions is broadly consistent with the literature maintaining that ICT through network possibilities decrease cost/traffic per minute associated with economic operations (Gille et al., 2002; Esselaar et al., 2007; Gutierrez et al., 2009; Gilwald & Stork, 2008). Moreover, further effects of ICT on CO_2 emissions might unveil in the future. It is essentially because these effects can be further increased in the future, that the positioning of the inquiry is based on how increasing ICT can affect CO_2 emission reduction.

Three caveats to the study are worth highlighting: First, the growing share of non-ICT sectors (such as technology involved in refrigeration and air conditioning) in GDP can also exert as much influence on CO_2 emission, as ICT-related factors. However, we restrict our study to ICT factors, owing to reasons already discussed in the introduction.

Second, a methodological handicap is the omission of the CO_2 emissions growth caused by anthropogenic deforestation and desertification in SSA. Within this framework some variables may need adjustment. For instance, the decrease of CO_2 absorbing capacity (caused by destroying the rainforests) could be calculated as a CO_2 equivalent and added to the CO_2 production from the burning of fossil fuels. Unfortunately, the variables used in the study were directly obtained from World Bank Development Indicators and no further transformations were done because we do not have the corresponding data with which to engage such transformations.

Third, the impact of ICT should intuitively be highly contingent on state policy-orientation. Unfortunately country-specific effects are not relevant in the modeling exercise because they are eliminated to limit the endogeneity which is associated with the correlation between the lagged endogenous variable and the error term. Moreover, African countries are treated as a homogenous group and the results are applicable to all the sampled countries for the same reason that country-specific effects are not engaged in the modelling framework. Hence, controlling for fundamentals like income levels, political stability and legal origins is also not feasible. While one might think that using sub-samples or these fundamentals (i.e. income levels, political stability and legal origins) could account for more idiosyncratic and group effects, the sub-sample estimations do not pass the post-estimation diagnostic tests because of instrument proliferation. It is important to note that the N>T condition is required for the application of the GMM technique. Sub-sampling decreases N and increases instrument proliferation. Moreover, even if these fixed effects or homogenous groups were to be considered in the modelling exercise, they are by definition eliminated in the GMM approach because they are correlated with the lagged dependent variable.

Future studies can build on these caveats in order to advance the extant knowledge, by employing alternative estimation techniques to assess whether the established findings withstand empirical scrutiny within country-specific settings and homogenous groups (e.g. income levels and legal origins). This would be necessary for more targeted policy implications.

Appendices

Appendix 1: Variable Definitions

Variables	Signs	Variable Definitions (Measurement)	Sources
CO_2 per capita	CO2mtpc	CO_2 emissions (metric tons per capita)	World Bank (WDI)
CO_2 from liquid fuel	CO2lfcon	CO_2 emissions from liquid fuel consumption (% of total)	World Bank (WDI)
Mobile phones	Mobile	Mobile phone subscriptions (per 100 people)	World Bank (WDI)
Internet	Internet	Internet penetration (per 100 people)	World Bank (WDI)
Trade Openness	Trade	Imports plus Exports of goods and services (% of GDP)	World Bank (WDI)
GDP growth	GDPg	Gross Domestic Product (GDP) growth (annual %)	World Bank (WDI)

Population growth	Popg	Population growth rate (annual %)	World Bank (WDI)
Educational Quality	Educ	Pupil teacher ratio in Primary Education	World Bank (WDI)
Regulation Quality	RQ	"Regulation quality (estimate): measured as the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development"	World Bank (WDI)

WDI: World Bank Development Indicators. CO_2: Carbon dioxide.

Appendix 2: Summary statistics (2000-2012)

	Mean	SD	Minimum	Maximum	Shapiro-Wilk	Observations
CO_2 per capita	0.901	1.820	0.016	10.093	0.709***	567
CO_2 from liquid fuel	78.880	23.092	0.000	100	0.842***	567
Mobile phone penetration	24.428	28.535	0.000	147.202	0.809***	525
Internet Penetration	4.222	6.618	0.005	43.605	0.634***	521
Trade Openness	76.881	35.326	20.964	209.874	0.918***	555
GDP growth	4.851	5.000	-32.832	33.735	0.853***	567
Population growth	2.334	0.866	-1.081	6.576	0.958***	529
Educational Quality	43.784	14.731	12.466	100.236	0.975***	425
Regulation Quality	-0.607	0.544	-2.238	0.983	0.983***	530

S.D: Standard Deviation. CO_2: Carbon dioxide. ***: 1% significance level.

Appendix 3: Correlation matrix (uniform sample size: 155)

CO2mtpc	CO2lfcon	Educ	Internet	GDPg	Popg	Trade	RQ	Mobile	
1.000	-0.721	-0.369	0.411	-0.057	-0.611	-0.0004	0.593	0.558	CO2mtpc
	1.000	0.246	-0.232	0.020	0.364	0.113	-0.366	-0.349	CO2lfcon
		1.000	-0.444	0.104	0.515	-0.147	-0.515	-0.403	Educ
			1.000	0.021	-0.580	0.256	0.536	0.718	Internet
				1.000	0.074	-0.136	-0.140	-0.128	GDPg
					1.000	-0.406	-0.624	-0.580	Popg
						1.000	0.128	0.270	Trade
							1.000	0.505	RQ
								1.000	Mobile

CO2mtpc: CO_2 emissions (metric tons per capita). CO2lfcon: CO_2 emissions from liquid fuel consumption (% of total). Educ: Quality of primary education. Internet: Internet penetration. GDPg: GDP growth. Popg: Population growth. RQ: Regulation Quality. Mobile: Mobile Phone penetration.

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